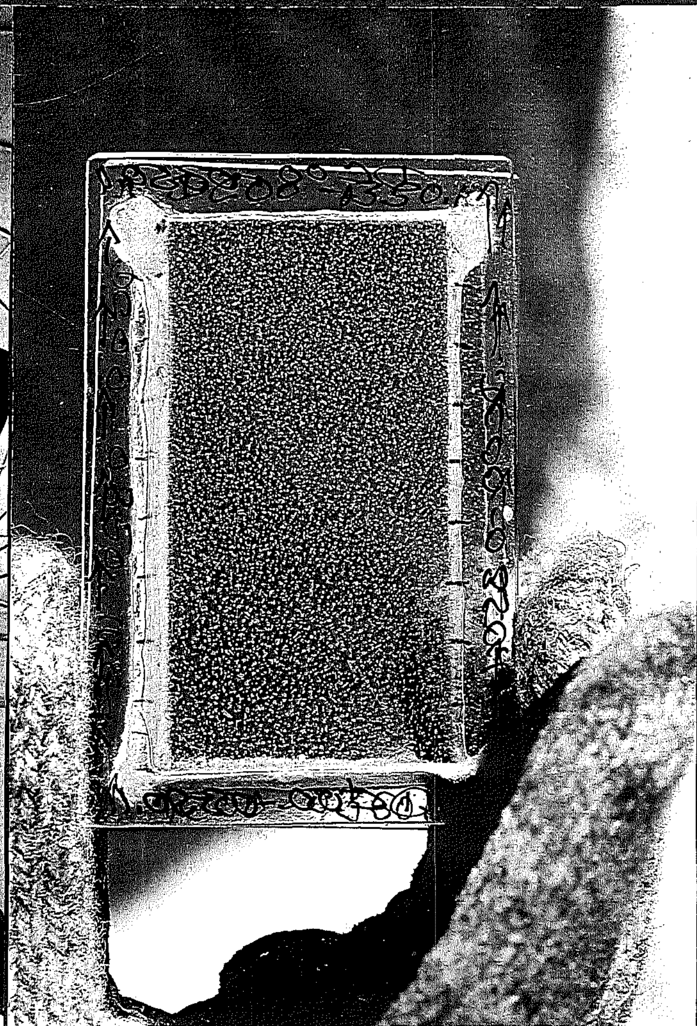

GCAS 2004-2005- Student : Lucia Sala Simion

The EPICA Project at Dome C

GCAS 2004-2005

Student: Lucia Sala Simion

Supervised Project

The EPICA Project at Dome C

(The European Project for Ice Coring in Antarctica)

INTRODUCTION

On Tuesday 21 December 2004, a European team involved in EPICA reached the drilling depth of 3270.2 m, which is 5m above the bedrock at Dome C, on the central plateau of the east Antarctic ice sheet. The ice is melting at the bedrock and it has been decided to stop at this depth to avoid any danger of direct contamination of the basal water. The drilling operation has therefore been terminated.

The drilling has been very successful and has been followed by a wide community of ice and climate researchers. The 70 meters of ice drilled this season completes a long venture started in 1996. The core has already led to the release in the scientific journal « Nature » last June of a 740,000-year record of Antarctic climate. The new piece of core will extend the record to an age estimated to be more than 900.000 years old.

This is the oldest ice that has been recovered from deep ice cores. The basal ice has ice crystals, some bigger than 40 cm and we have observed many inclusions of brown/reddish material mainly between the big ice crystals.

The prospect of the new and unknown information to be found by studies of the ice from the EPICA DomeC ice core is fascinating and may have a profound impact on our understanding of the Earth's climate and environment.

As a freelance science journalist and photographer I have documented the EPICA project at Dome C in the 2000-2001, 2001-2002 and 2002-2003 summer campaigns, thanks to the help of the Italian Polar Programme. This is a report on the EPICA project in words and pictures. A VHS PAL cassette with some video footage of the drilling operations is included.


EPICA DOME
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3000m
EPICA DÔME C
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3270.20m 21'12'2004

EPICA (European project for Ice coring in Antarctica) is an ambitious programme to drill deep cores in two different regions of Antarctica. The aim is to achieve optimal resolution at different time scales, and to obtain a broader perspective relating to the Antarctic continent as a whole. However, to ensure that logistic operations and also the ice core analysis capabilities of European laboratories are not overloaded, the two sites were drilled consecutively, splitting the programme into two halves.

The first phase, lasting five years, was focused on the longer time period spanning the last few glacial to interglacial cycles going back ~900,000 years. To do this, a 3,270 metre long core was drilled at Dome C south of the Indian Ocean in East Antarctica, location of the French-Italian station Concordia (MZS at terra Nova Bay is 1.200 Km to the North-East and Dumont d'Urville station is 1.100 Km to the north).
The exact drilling site was selected with a geodetic and geophysical survey in the austral season 1995-96 to single out the thickest and least disturbed ice sequence, in order to obtain a long and continuous climate record. This is also an excellent location for setting the whole Antarctic record into a global context, in particular enabling comparisons with the Greenland record in the north, and with long continental and ocean records from all over the globe.

While this first phase was taking place at Dome C, a detailed geophysical and geochemical reconnaissance was made in Dronning Maud Land, to identify optimal sites for deep drilling. This region of Antarctica is most strongly influenced by the Atlantic ocean, and was chosen because the cores obtained here, in a region of higher snow accumulation rate, will provide finer grained detail on the last glacial cycle.

A particular goal is to investigate in detail the climatic changes in Antarctica during the sequence of rapid climate oscillations recorded in the GRIP core from Greenland during the last glacial, and to study evidence for time-phase differences between events recorded in the two hemispheres. The Dome C core will have inadequate resolution to resolve this issue for the last glacial cycle, although significantly it will help establish whether similar events occurred in earlier glacial cycles.

This is one of the biggest tests yet of the ability of European laboratories to cooperate in a large complex project. However, the ice-core laboratories involved have already learnt to integrate their research efforts within GRIP, and this is an opportunity for them to consolidate this as a basis for an emerging European network for Antarctic and Arctic activities.

The **EPICA project** has been motivated primarily by the urgent need to predict more accurately how global climate is likely to respond to increased emissions of greenhouse gases as a result of human activities. In order to predict the future, it is necessary to determine how global climate has responded to variations in greenhouse gas concentrations in the past, in combination with other forcing factors such as changes in solar output and in the earth's orbit.

The polar ice sheets are the only archive preserving information about changes both in past climate and in the atmosphere's composition. Valuable information covering at least a full climatic cycle (the last 150,000 years) has already been obtained from deep ice cores drilled through the Greenland and Antarctic ice caps. However, the Antarctic ice sheet spans an area comparable to the size of Europe and it covers a correspondingly wide range of both climatological and glaciological regimes. No single site can deliver a climate record that is representative of the whole continent, nor yield a record that has optimal resolution across the whole time range of interest. New high resolution records from Antarctica are needed to complement the records recently obtained in central Greenland. There is also a need to go back further in time to ascertain whether recent patterns are relatively unique, or typical of other climatic cycles.

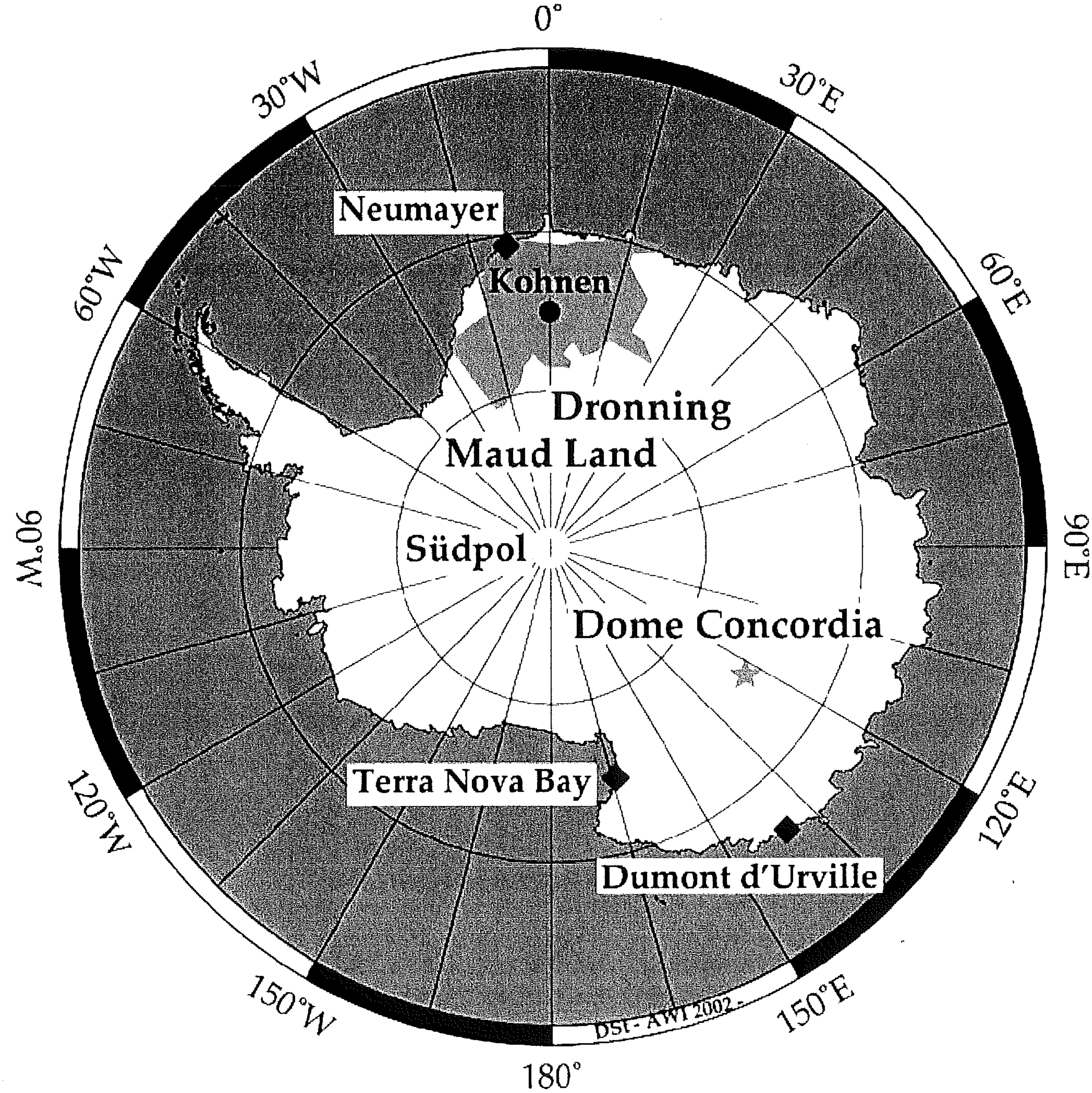
EPICA has been developed in collaboration with the European

Commission to meet these objectives. Fresh technical challenges have to be overcome, mainly due to the much lower temperatures in continental Antarctica compared with Greenland, and the necessity to work in unexplored regions, requiring extensive meteorological and geophysical work to select drill sites. A new drill was designed, built and tested in North Greenland, drawing on the designs of drills used successfully in the Greenland Ice Core Project (GRIP) and by Japan in central East Antarctica.

Drill sites:

EPICA's goal is to retrieve two ice cores from different regions on the Antarctic ice sheet which are especially selected to answer specific questions. The first core was drilled at Dome C (coordinates in WGS 84: 75 ° 06.10' S, 123° 23.71', 3233 m) in the Indian Ocean sector of the East Antarctic plateau. Dome C is the location of the French-Italian station CONCORDIA.
This core hold the longest ice core record on earth providing a history of detailed climate and atmospheric changes over the last 900,000 years.

The second core was drilled in Dronning Maud Land (coordinates in WGS84: 75 ° 0.10' S, 0° 4.07' E, 2882 m) in the Atlantic sector of Antarctica covering more than a complete glacial cycle. The location is called Kohnen station. The dominant influence of air masses originating over the southern Atlantic to this site will allow to investigate the coupling of the northern and southern hemisphere in detail. Furthermore the higher accumulation rate encountered in this region enables to reconstruct high resolution climate records over the last 160,000 years.
Accordingly, it represents a direct counterpart of the central Greenland ice core records and is ideal to study the occurrence of rapid climate changes.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Kohnen
Dronning
Maud Land
Südpol
Dome Concordia
Terra Nova Bay
Dumont d'Urville
DSt - AWI 2002 -

The EPICA Scientific Steering Committee

The EPICA Scientific Steering Committee (SSC) was formally established in October 1995. It is formed of national representatives (one per country), representatives of the two Logistic Operation Centres, the leaders of the Working Groups (Science Working Group, Finance Panel, Drilling Working Group), and the representatives of ESF and EU. The SSC is currently chaired by H Miller with J Jouzel as Vice-chair and meets once a year. An Executive Committee (ExCom), comprising the EPICA chair and Vice-chair, heads of the two Operation Centres and the leaders of the Working Groups, meets twice a year.

Current members:

Professor Heinz Miller (Chair)
Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

Dr. Jean Jouzel (Vice Chair)
Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS, Gif sur Yvette, France

Dr. Hans Brelen
European Commission, Brussels, Belgium

Dr. Antonino Cucinotta (OC1)
ENEA Progetto Antartide, Bologna, Italy

Dr. Hartwig Gernandt (OC2)
Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

Dr. Margareta Hansson
Department of Physical Geography and Quaternary Geology, University of Stockholm, Sweden

Dr. Gérard Jugie (OC1)
Institut Polaire Français Paul-Emile Victor (IPEV), Plouzané, France

Dr. Hans Oerter
Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

Professor Valter Maggi
Environmental Science Dept. (DISAT), University of Milano Bicocca, Milan, Italy

Dr. Dominique Raynaud
Laboratoire de Glaciologie et de Géophysique de l'Environnement, St. Martin d'Hères, France

Dr. Jean-Jacques Reyser (finance panel)
Institut Français pour la Recherche, Plouzané, France

Professor Roland Souchez
Département des Sciences de la Terre et de l'Environnement, Université Libre de Bruxelles, Belgium

Dr. Joergen Peder Steffensen
Department of Geophysics, University of Copenhagen, Denmark

ProfessorThomas Stocker *(from April 2003)*
Physikalisches Institut der Universität Bern, Switzerland

Dr. Jakob Schwander (Drilling Group) *(from April 2003)*
Physikalisches Institut der Universität Bern, Switzerland

Dr. Michiel van den Broecke *(from April 2003)*
Institute for Marine and Atmospheric Research, Utrecht, The Netherlands

Dr. Jan Gunnar Winther
Norwegian Polar Institute, Tromso, Norway

Dr. Eric Wolff (Science Group)
British Antarctic Survey, Cambridge, United Kingdom

<u>European Science Foundation:</u>

Dr. Martina Hildebrandt
Scientific Secretary

Pat Cosgrove
Administrator

Members of the EPICA Steering Committee stepping down during 2003

Professor Giuseppe Orombelli (Co-Vice Chair) *(to August 2003)*
Dipartimento di Scienze dell'Ambiente e del Territorio, Università di Milano, Italy

Professor Johannes Oerlemans *(to April 2003)*
Institute for Marine and Atmospheric Research, Utrecht, The Netherlands

Professor Bernhard Stauffer (Science Group) *(to April 2003)*
Physikalisches Institut der Universität Bern, Switzerland

Dr. Mario Zucchelli (OC1) *(to October 2003 - obituary)*
ENEA, CRE Casaccia, S. Maria di Galeria (RM), Italy

Participating institutions:

* Dipartimento di Scienze dell'Ambiente e del Territirio, Università degli Studi di Milano, Italy.

* Laboratoire de Modelisation du Climat et de l'Environnement (LMCE/DSM), France.

* Alfred-Wegener-Institute for Polar and Marine Research, Bremerhaven, Germany

* Niels Bohr Institute, Department of Geophysics, University of Copenhagen, Denmark.

* Dept. of Meteorology, Stockholm University, Sweden.

* Institut Polaire Français Paul-Emile Victor (IPEV), France.

* Laboratoire de Glaciologie et Geophysique de l'Environnement, France.

* Laboratoire de Glaciologie et Geophysique de l'Environnement du CNRS, France.

* Institute of Marine and Atmospheric Research (IMAU),

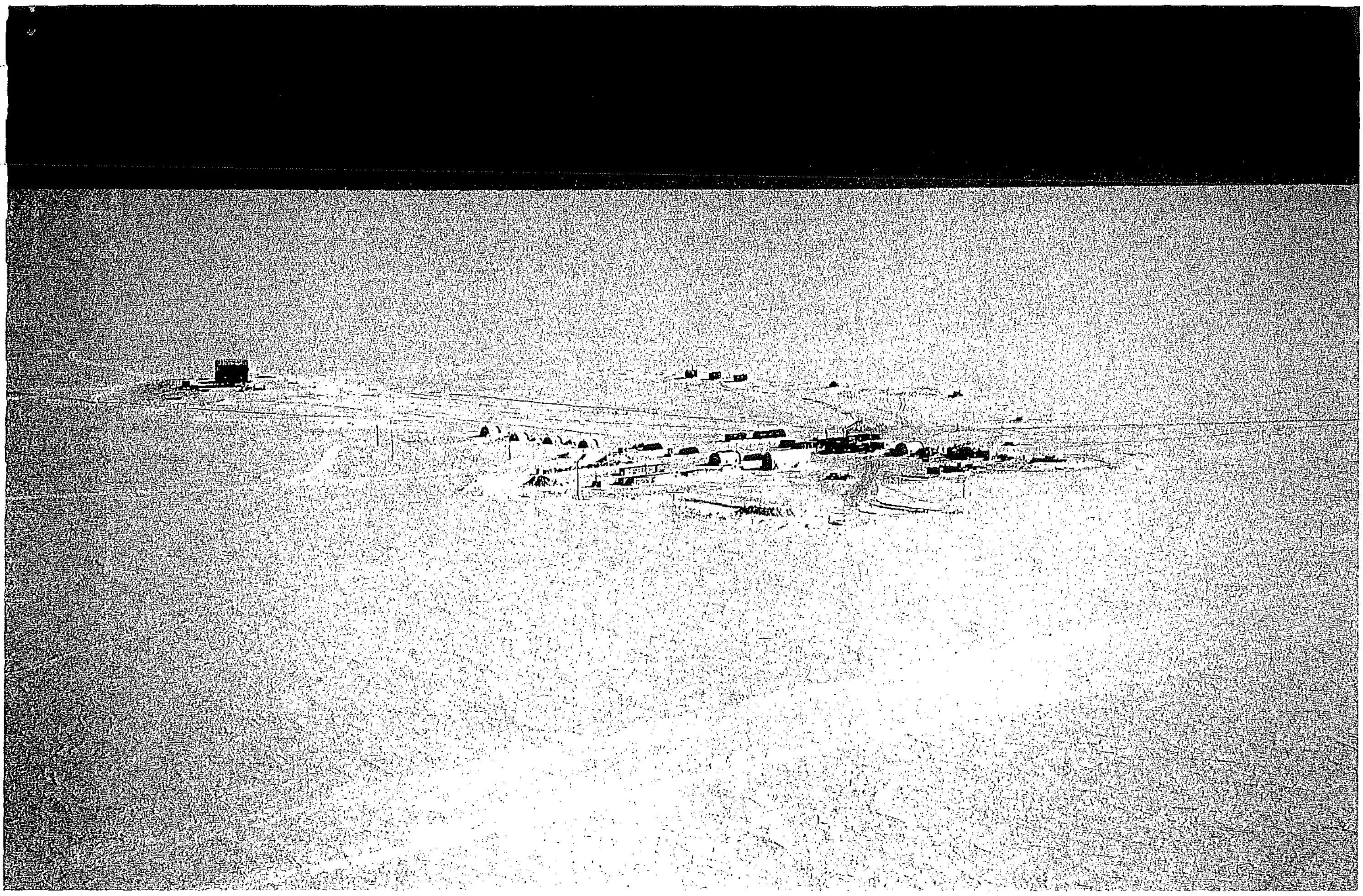
University of Utrecht, Netherlands.

* British Antarctic Survey, United Kingdom.

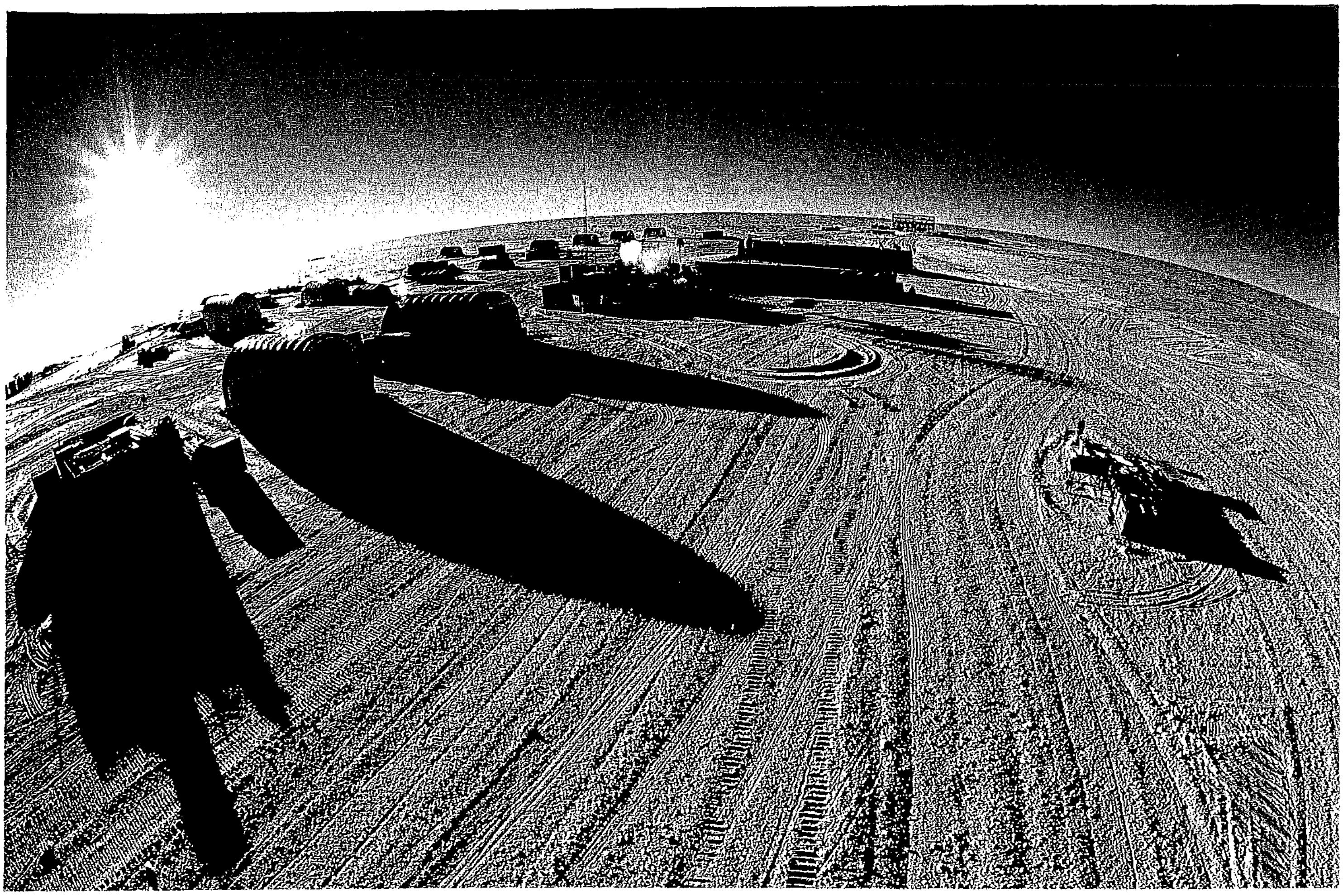
* Dept. des Science de la Terre et de l'Environnement,
Section Glaciologie, Universite Libre de Bruxelles, Belgium.

* Physikalisches Institut der Universität Bern, Switzerland.

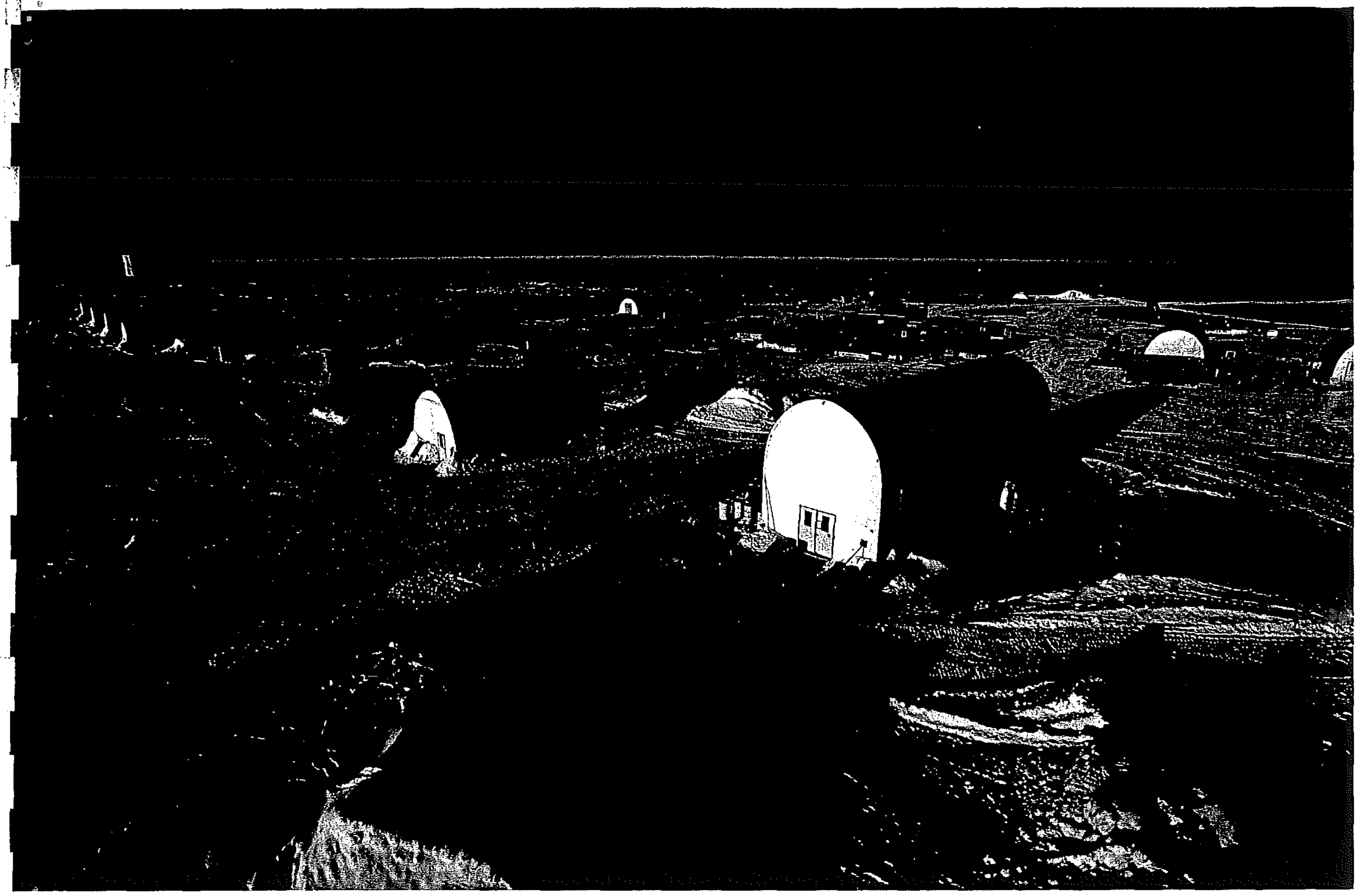
* Norwegian Polar Institute, Norway.



The summer camp at Dome C, Latitude: 75° 06′ South - Longitude: 123° 23′ East. The Concordia station is on the left. **Ph. Lucia Simion**



The summer camp at Dome C, Latitude: 75° 06′ South - Longitude: 123° 23′ East. The Concordia station is in the background. The first winter-over in the French-Italian station began February 10th, 2005. Mario Zucchelli Station at Terra Nova Bay is 1.200 Km to the North-West, Dumont d'Urville 1.100 km to the North. **Ph. Lucia Simion**



The summer camp at Dome C, Latitude: 75° 06′ South - Longitude: 123° 23′ East. The tallest tent is the EPICA drilling tent, nicknamed "The Cathedral". **Ph. Lucia Simion**

The single most important source of information about past climate change and the associated composition of the atmosphere are the two large ice caps of Greenland and Antarctica. Analysis of ice cores is therefore the most powerful means we have to determine how climate has changed over the last few climate cycles, and to relate this to changes in atmospheric composition, in particular to concentrations of the principal greenhouse gases - CO_2, CH_4 and N_2O (carbon dioxide, methane, and nitrous oxide).

Recent deep-drilling efforts have focused more on central Greenland, notably the highly successful ESF Greenland Ice Core Project (GRIP) and the US Greenland Ice Sheet Project (GISP2) at Summit. Studies of the vast East Antarctic plateau have so far been limited to a single core obtained at Vostok and to a recent drilling by the Japanese at Dome Fuji, neither of which have reached bedrock. EPICA was designed to complement the Greenland projects, and determine whether some of the results obtained from these earlier studies have global significance or are confined chiefly to the Arctic region. It also aims to achieve one of the longest possible climate records from Antarctica, at a site where the record is likely to require minimal correction for ice flow, by drilling to bedrock at an ice dome (Dome C).

EPICA's two broad objectives were firstly to obtain a full documentation of the Antarctic climate record and then to compare this as optimally as possible with the Greenland record. To do this two more cores were needed to cover the extremes of time scale, with one at a site of higher annual snowfall to provide a detailed record of events over the last glacial cycle, and the other in a region of low snow accumulation to allow changes over several glacial cycles to be recorded at a lower resolution.

Furthermore, the complex structure of the atmosphere over Antarctica, and its interactions with the surrounding ocean, make it necessary for ice cores from several locations to be analysed (i.e. the two EPICA cores plus the earlier ones) in order to achieve a continental perspective. Taken together the two cores are expected to shed light on the following key questions not answered by the results from either the Greenland cores, or the earlier Vostok drilling in Antarctica.

1. Are the rapid climatic changes of the last ice age cycle global events, or are they restricted largely to part of the Northern Hemisphere, where it is possible that geographic conditions favour them?

2. Are these rapid changes unique to the last glacial cycle or did they occur in previous cycles as well?

3. Is the relatively warm stable climatic period of the last

10,000 years an exception for the last 500,000 years?

4. Do the transitions from the glacial to warm periods and back again always follow the same pattern or is a variety of mechanisms involved?

5. Are global climate changes always triggered in the northern Hemisphere or is the opposite sequence possible?

6. How are global climate changes coupled between the two hemispheres?

The answers to all these questions have an important bearing on the ability to predict future climate, and in particular to assess the impact of anthropogenic effects. The archives obtained from the cores will also provide unique evidence on the role of the different elements in the climate equation, including forcing factors (greenhouse gases etc), climate variability, and long term climate/ice sheet interactions. In addition, the ice cores will tell us more about the history of the ice sheet itself, which is very relevant to our understanding of sea-level rises.

The ultimate prize is to obtain as full an understanding as possible of the mechanisms driving both global climate change and the coupled biogeochemical cycles, to give the required perspective for assessing current and imminent changes. To reach this understanding it is necessary to study past changes over several different time scales, which **EPICA** is therefore doing. The Atlantic sector site will encompass the last climatic cycle in detail to examine processes responsible for short term fluctuations of the type observed from the Greenland cores. The snow accumulation rate there is sufficiently high for changes to be resolved at least down to the scale of individual seasons. By contrast, the Dome C site will cover at least 8 glacial cycles, with the aim here being to compare the processes of major climate change in each case. However, the resolution should still be high enough to ascertain whether the rapid oscillations observed at times of climate change during the last cycle also occurred in earlier cycles.

Scientific background

There is widespread concern that emissions of carbon dioxide and other greenhouse gases will cause a significant rise in global air temperatures by the middle of the next century. But although there is little doubt that there is a close relationship between atmospheric greenhouse gas levels and global temperature, there is still great uncertainty over the likely extent and speed of the changes, and how they will be distributed regionally.

There are two principal findings from earlier ice core studies in central Greenland and Vostok, Antarctica, that need further confirmation and extrapolation back in time. The first is the expected close correlation between climate and greenhouse gas concentrations extending back to 240 ka, as indicated by the ice core record from Vostok.

On the other hand, the second finding from central Greenland ice cores was much less expected, confirming a series of large and rapid oscillations in climate during the late part of the last glacial period and during the transition, which occurred within the time span of a human lifetime. Then, just as unexpected, was the revelation from the GRIP isotopic and chemical record that similar oscillations may have occurred during the last interglacial 110 -140 ka ago. However, although the GRIP and

GISP2 records match almost exactly back to 110,000 years ago, below this depth significant structural disturbances are observed in both cores, and the records start to diverge. Most probably, one or both records has been affected by flow disturbances in the lowest part of the ice sheet.

Ice drill programmes have the twin goals of identifying changes in past climate and in atmospheric chemistry. One of the principal ways of identifying climate change is to determine the proportions of the stable oxygen 18 and deuterium (hydrogen 2) isotopes at different levels of the core through their presence in water. As HDO and H218O are heavier molecules than standard H216O, they have a slightly lower saturation vapour pressure than the lighter ones, and the proportions observed in precipitation change as an air mass becomes depleted as it moves polewards from source regions over the oceans. As a result, there is an approximately linear relationship between the mean isotopic content of snow and the mean annual temperature, although additional influences relating to conditions in the source region of the air masses providing the Antarctic precipitation need to be considered.

Equally important is to reconstruct the record of past atmospheric chemistry, including aerosols and water soluble gases, in addition to the composition of atmospheric gases trapped in bubbles within the ice. A variety of techniques is used here, including continuous flow analysis to measure H2O2, NH4, and HCHO. Sodium, calcium and sulfate levels are also measured, as these provide information, respectively, on past atmospheric concentrations of sea salt (Na), soil dust (Ca), and secondary aerosols derived from sulphur, including marine biogenic and volcanic emissions.

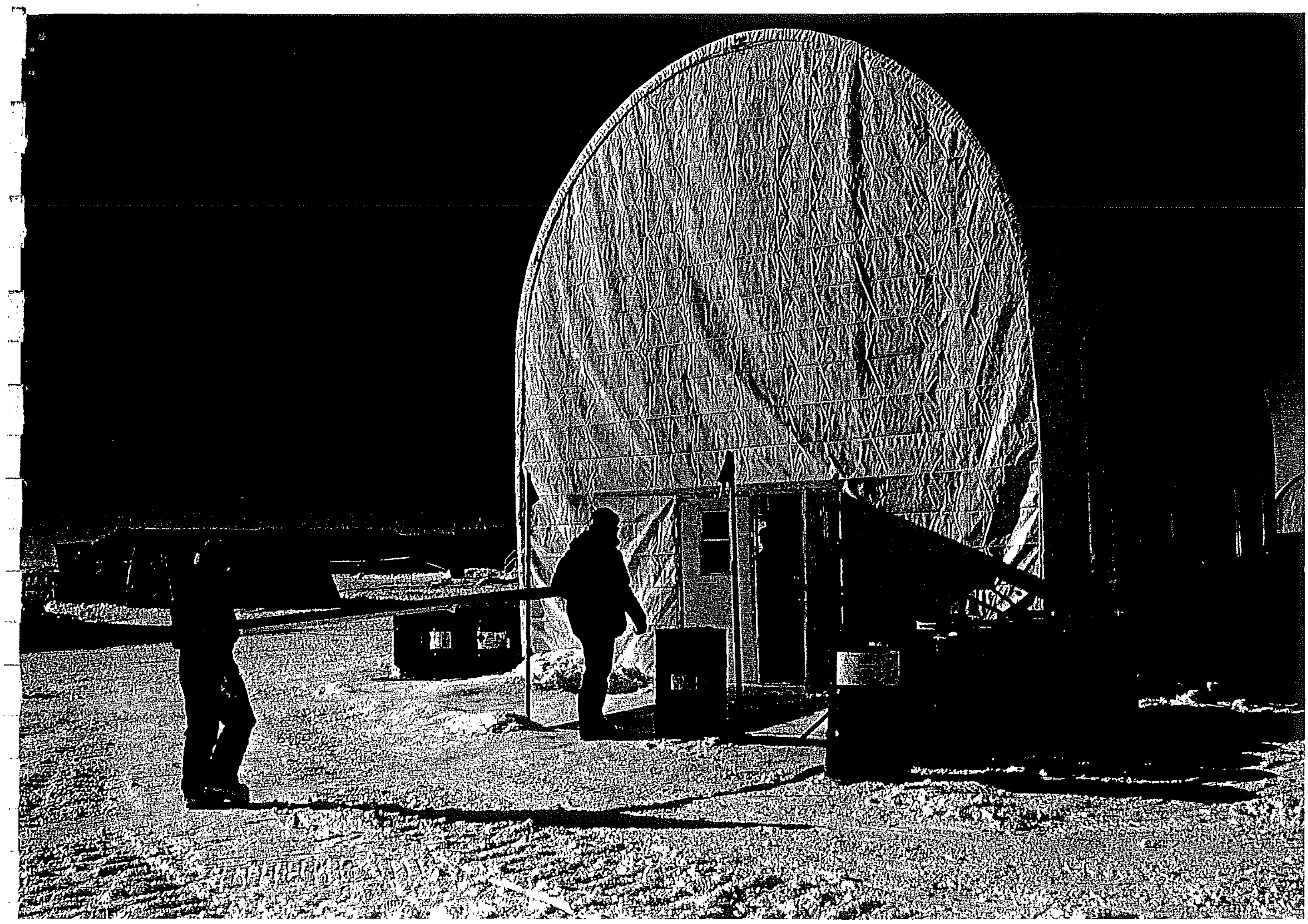
All these measurements would be of little value, however, without accurate dating of the ice cores. For the last 50 ka this is relatively straightforward, as detailed information has already been obtained from Central Greenland cores (GRIP and GISP2) and from a core obtained in the western Antarctic deep Byrd ice. Dating of the new cores can then be performed by matching acidic sulphur signals against volcanic horizons identified within the Byrd core. To extend the dating back to 250,000 years other techniques are needed, and include ice-flow modelling controlled by matching features in the new cores (eg. changes in atmospheric gas isotopic and chemical composition) with corresponding features in the ice cores from Vostok and central Greenland as well as with the ocean sediment records.

In this regard, developments in the ESF's European Ice Sheet Modelling Initiative are expected to provide improved methods for dating the cores and separating climatic signals from ice-sheet signals (i.e. changes in topography/ice flow).

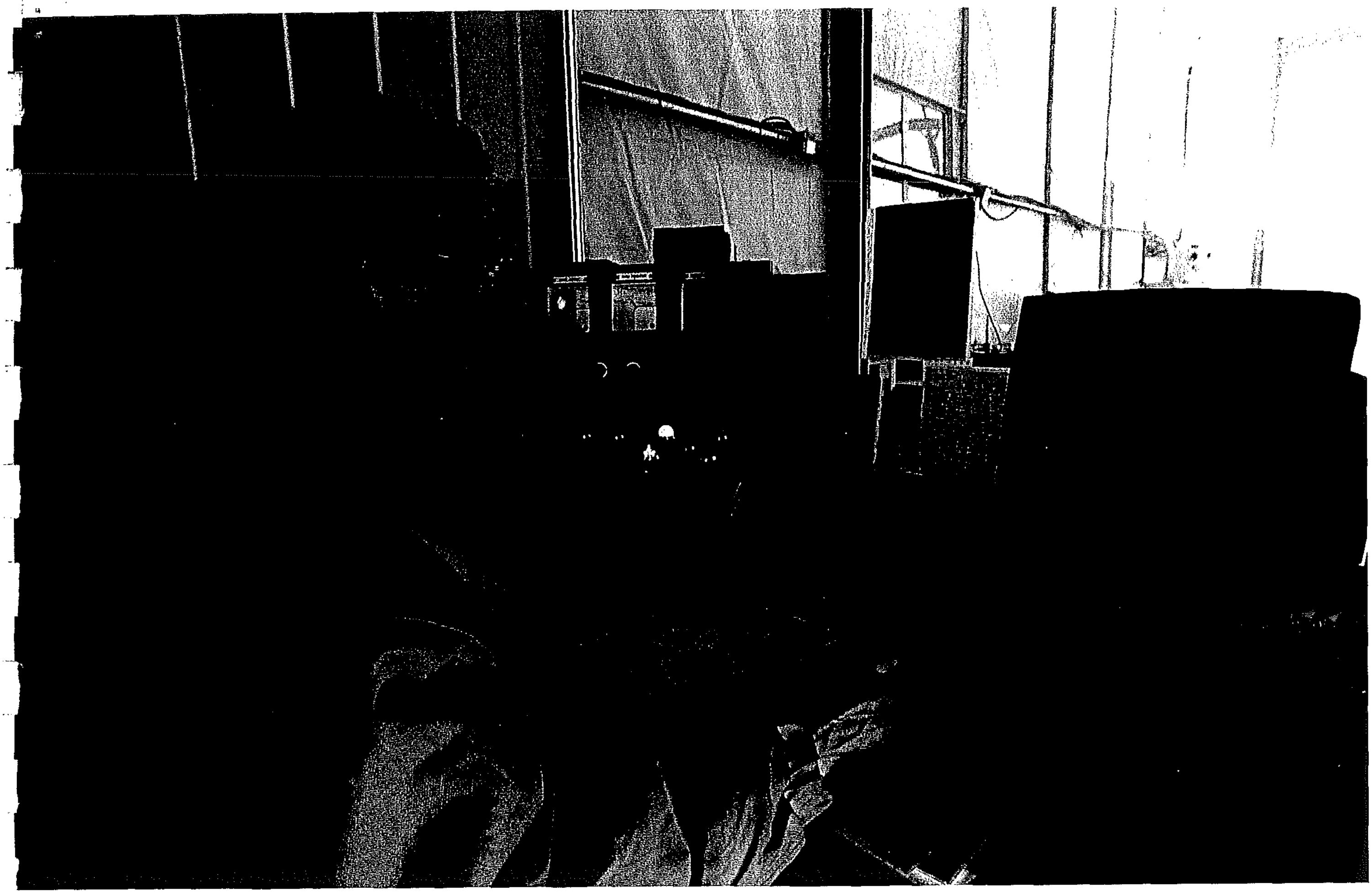
Records from Vostok, Antarctica, have shown a close correlation between climate and greenhouse gas concentrations that now extends to 240 ka. The central Greenland cores obtained by GRIP, and also by GISP 2 (Greenland Ice Sheet Project) have confirmed the existence of rapid and large oscillations during the last glacial period and the end of the last transition (between ice age and current warmer period). One interesting question that EPICA can help determine is whether these oscillations were a global phenomenon, or confined to a large part of the Northern Hemisphere where geographical conditions might favour them.

Other important questions that EPICA should help answer include whether the climatic stability of the last 10,000 years, which contrasts with extreme climate variability through most of the rest of the last glacial, is an exception for the last 500,000 years, and how global climate changes are coupled between the two hemispheres.

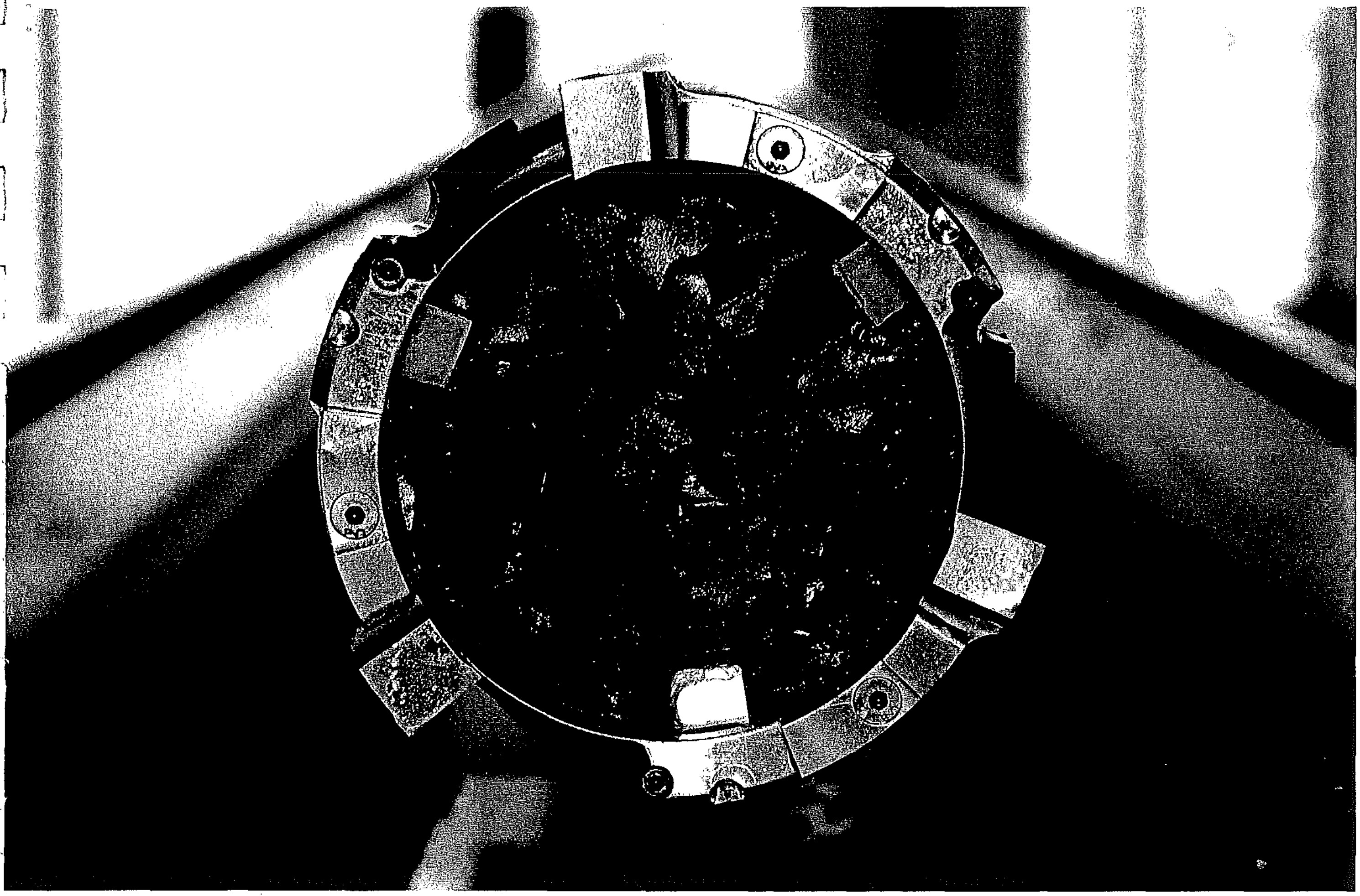
The costs of the first phase of EPICA was 20 MEcus (13 MEcus for the deep drilling at Dome C and 7 MEcus for the Dronning Maud Land Reconnaisance). More than 40% (8.5 MEcus) has been funded by the Climate and Environment programme of the European Commission (Framework Programme IV). A third contract will provide support during the period May 2001-April 2003. The rest of EPICA costs are covered by national contributions from: **Belgium, Denmark, France, Germany, Italy, The Netherlands, Norway, Sweden, Switzerland and the United Kingdom.**



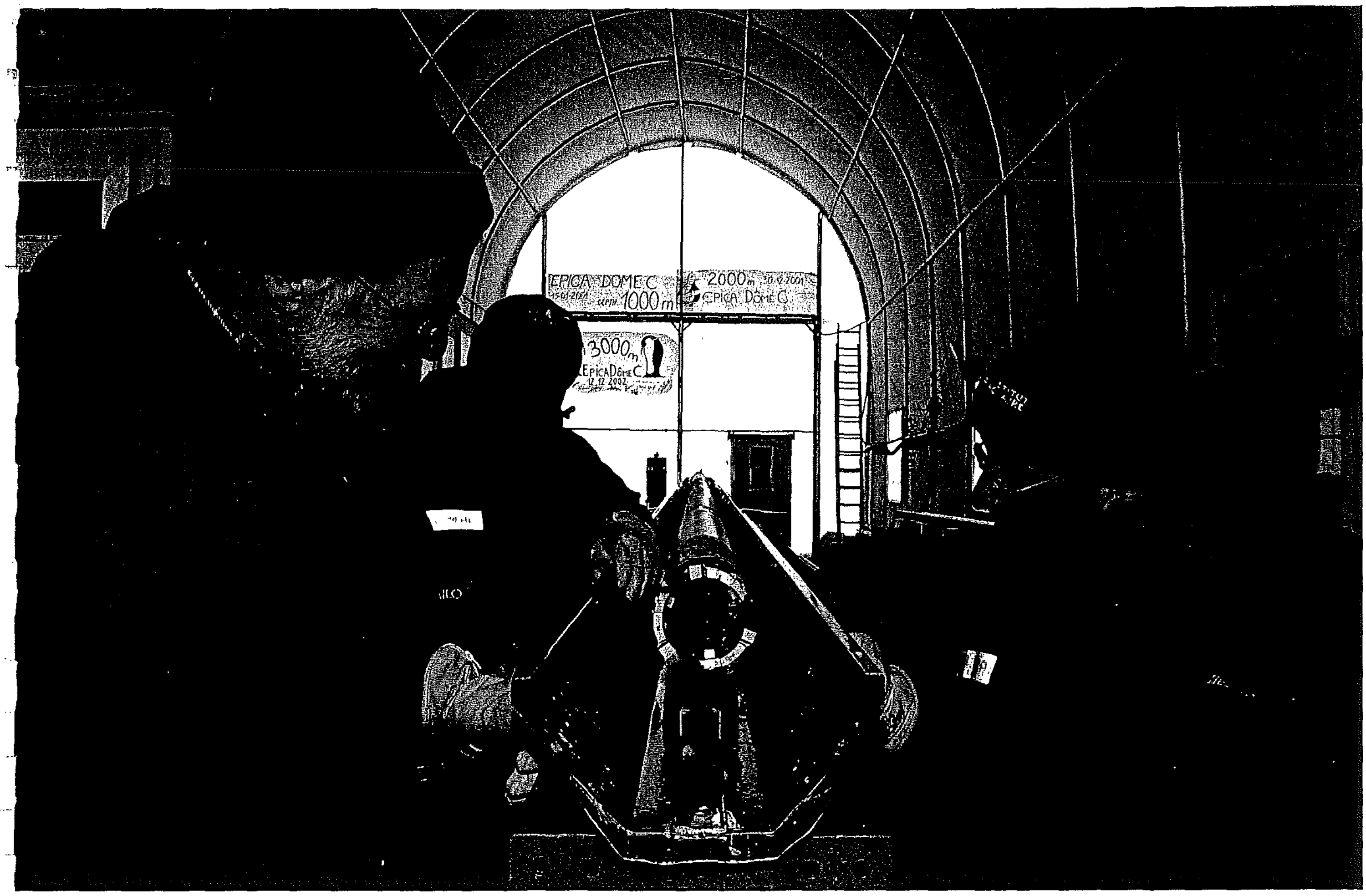
The summer camp at Dome C, Latitude: 75° 06′ South - Longitude: 123° 23′ East. Two drillers enter the EPICA drilling tent, nicknamed "The Cathedral". **Ph. Lucia Simion**



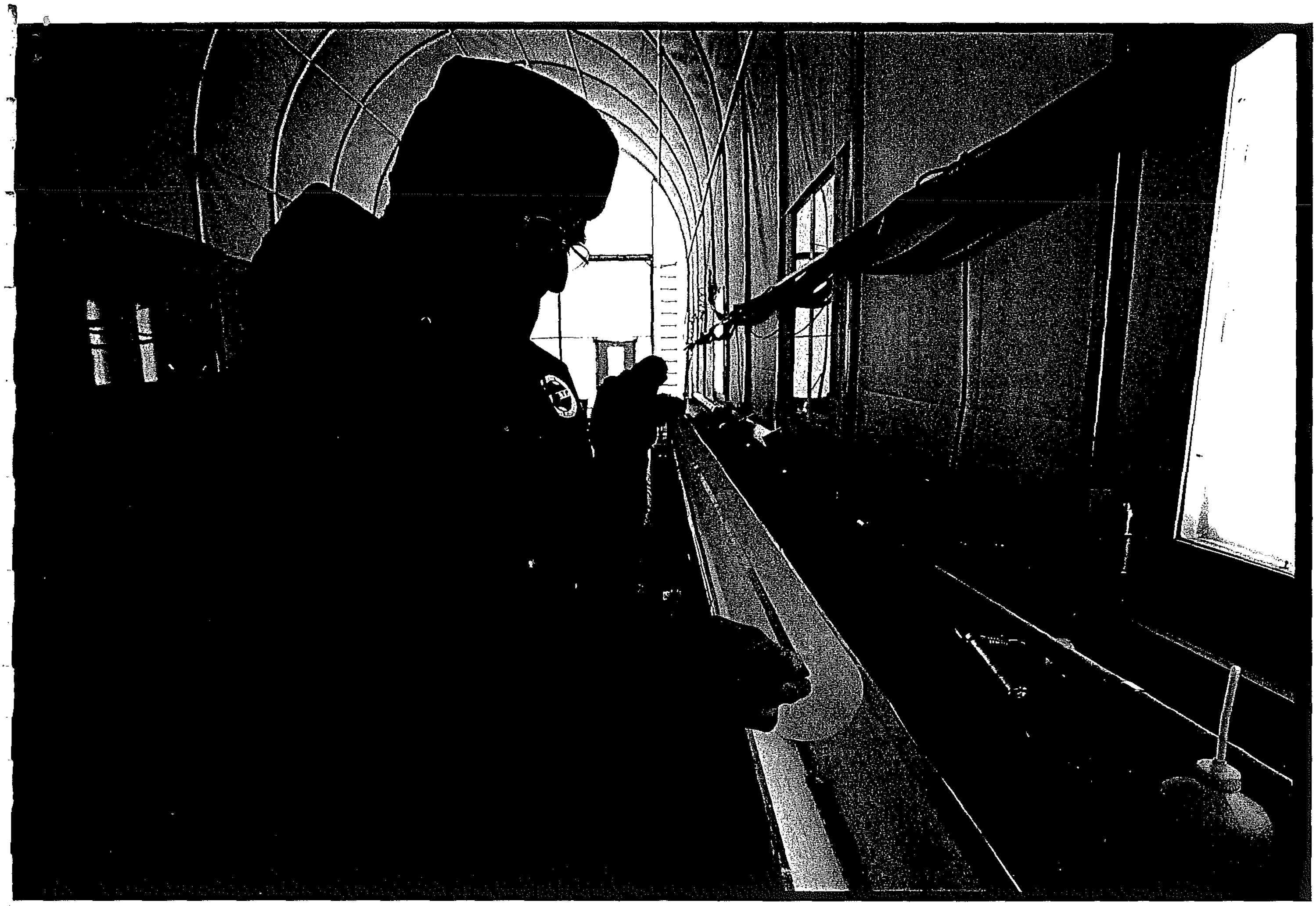
Alain Manouvrier, driller with the Laboratoire de Glaciologie et de Geophysique de l'Environnement (LGGE) in Grenoble, France inside the EPICA drilling tent. He is in front of the control panel in the operations room. A "run" is under way: this means that the drilling device is going down inside the ice cap, drilling out an ice core. The "run" is controlled by computer from the operations room. **Ph. Lucia Simion**



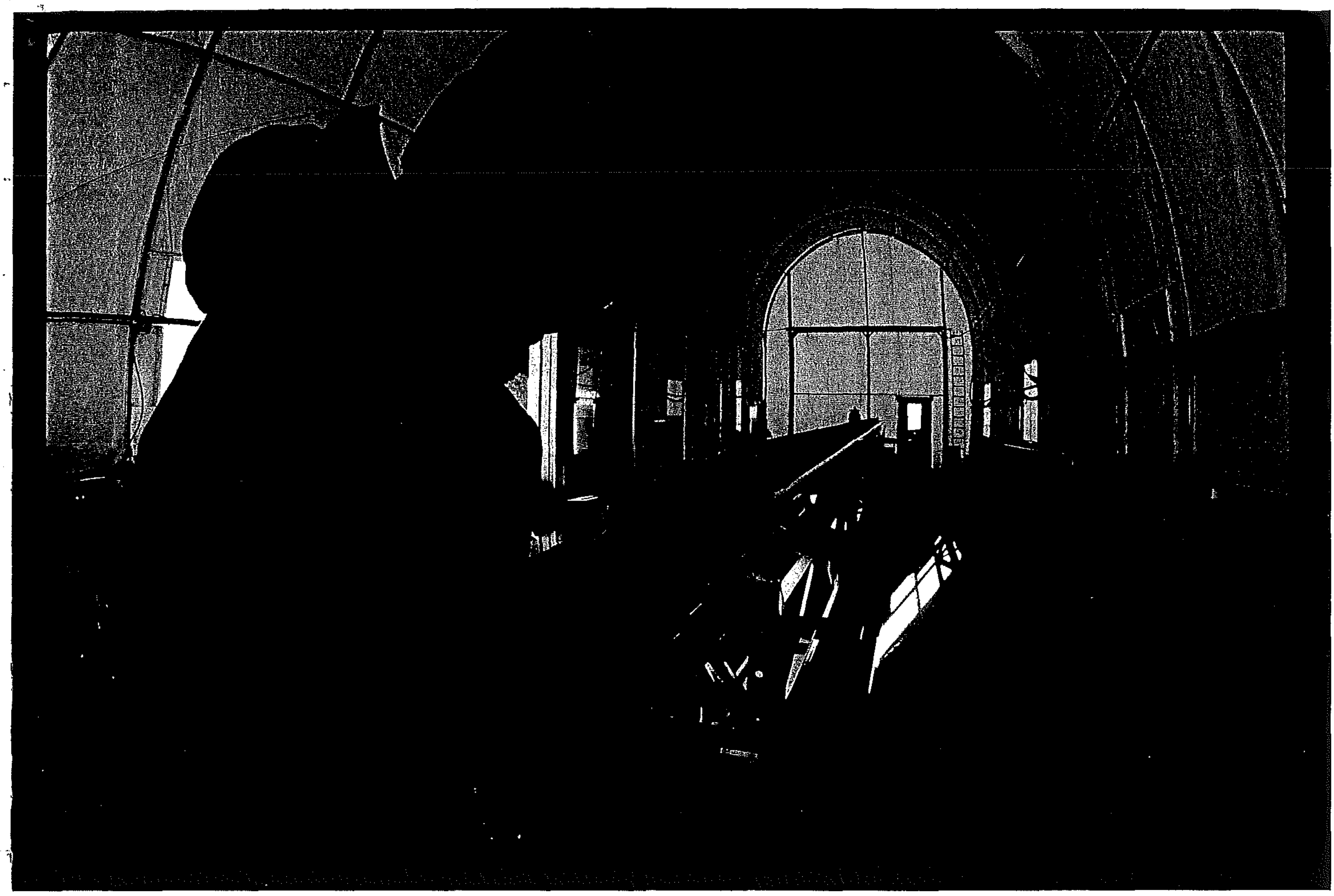
An ice core from Dome C, inside the drilling device. The ice crystals are extremely large. Ice cores are ice cylinders 10 cm in diameter, that are gradually retrieved in segments of up to 3 m length during the drilling process. Ultimately, this ice originates from snowflakes falling over hundreds of thousands of years. In the process of falling, flakes collect aerosol particles from the air. Over time, snowflakes are transformed into ice crystals, encapsulating the air between them, together with minute particles, in small bubbles. **Ph. Lucia Simion**



Three drillers are looking at an ice core still inside the drilling device.
Ph. Lucia Simion

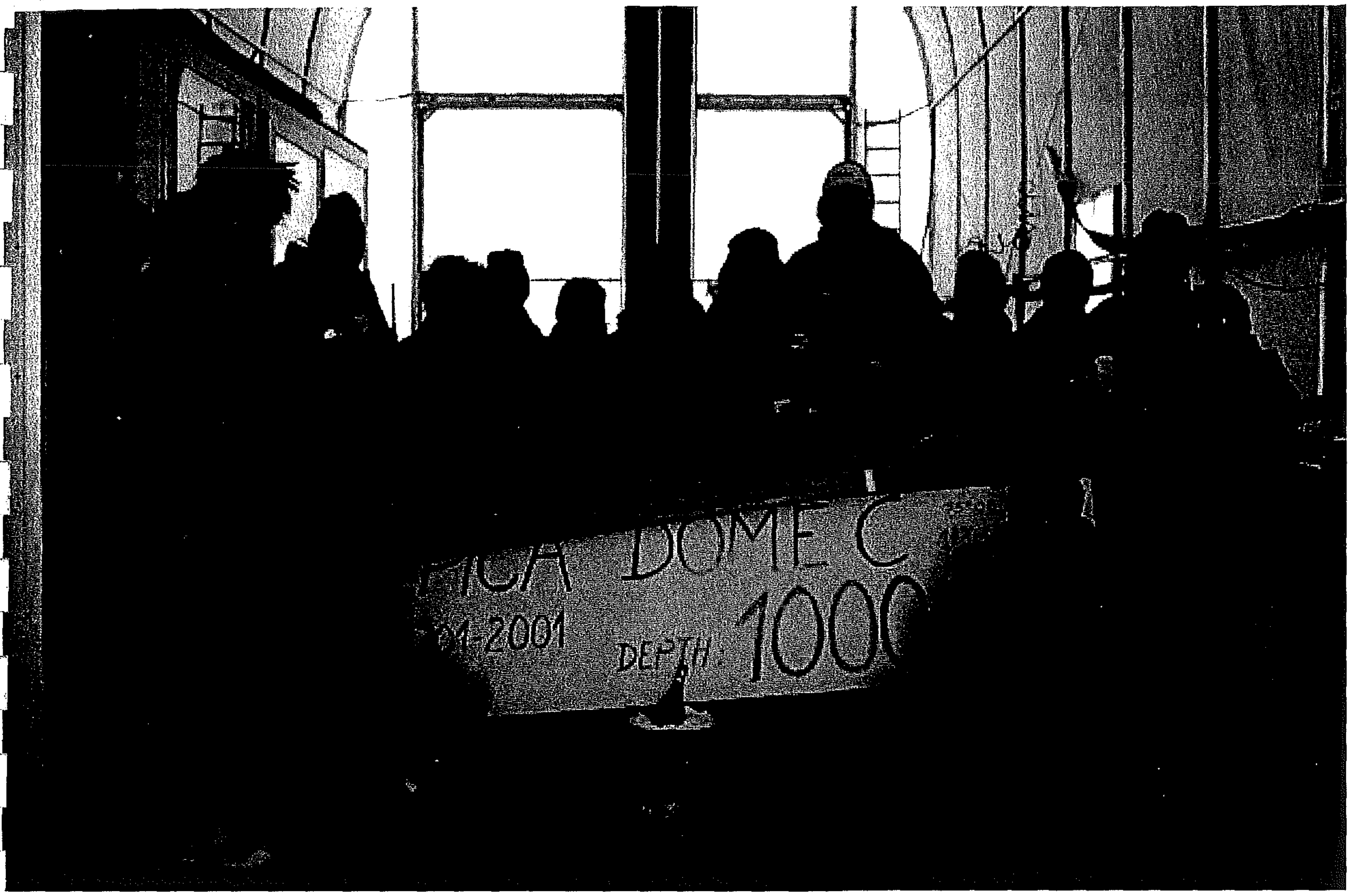


Alain Manouvrier (FR) and Fabrizio Frascati (ITA) measuring the lenght of an ice core. **Ph. Lucia Simion**

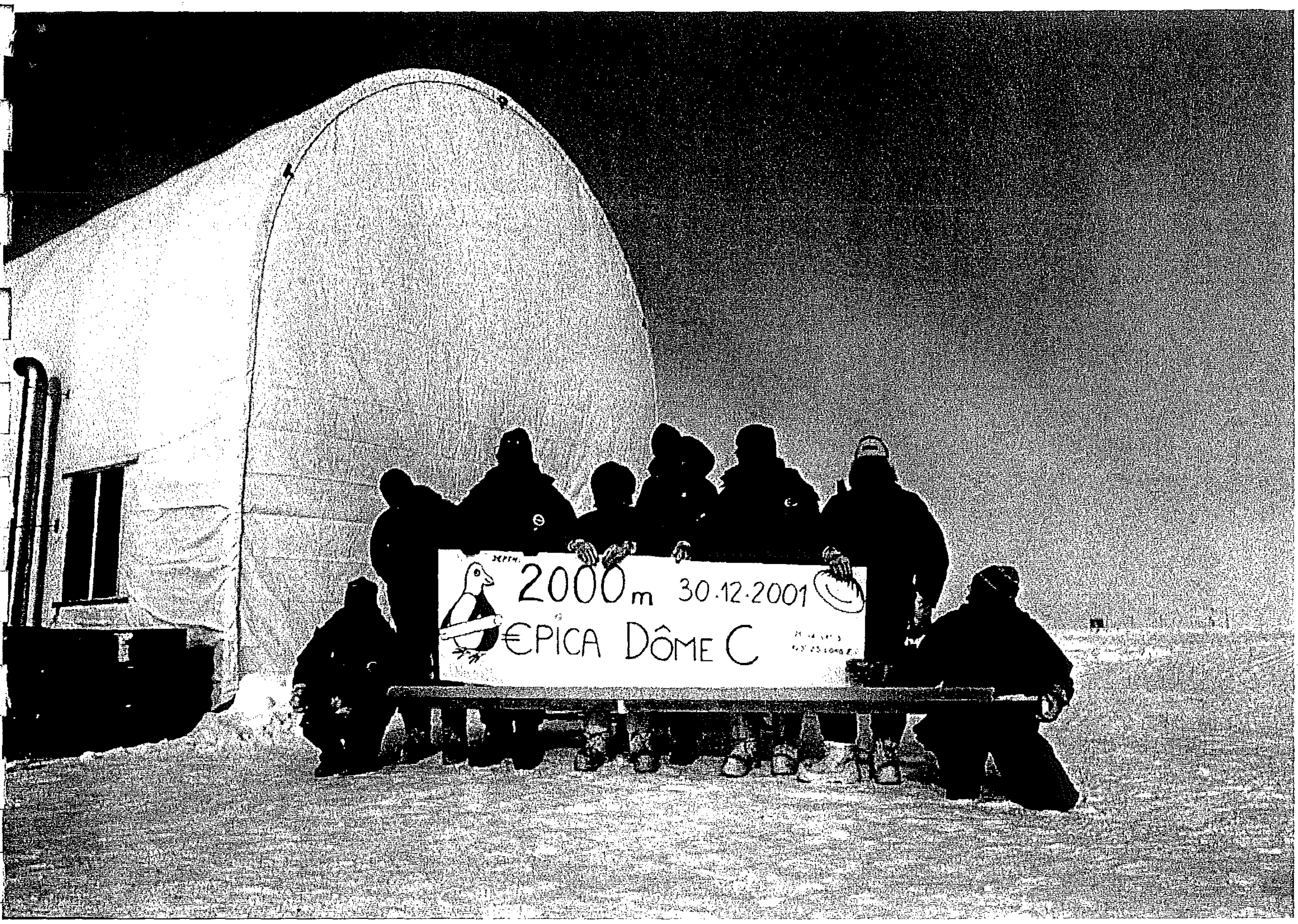


Checking the cutting blades of the drilling device prior to a "run".
Ph. Lucia Simion

Dome C, January 11, 2001: the EPICA project drillers celebrating the reached depth of 903,5 m. Ph. Consorzio PNRA



Dome C, January 2001: the EPICA project drillers and glaciologists celebrating the reached depth of 1.000 m. Ph. Consorzio PNRA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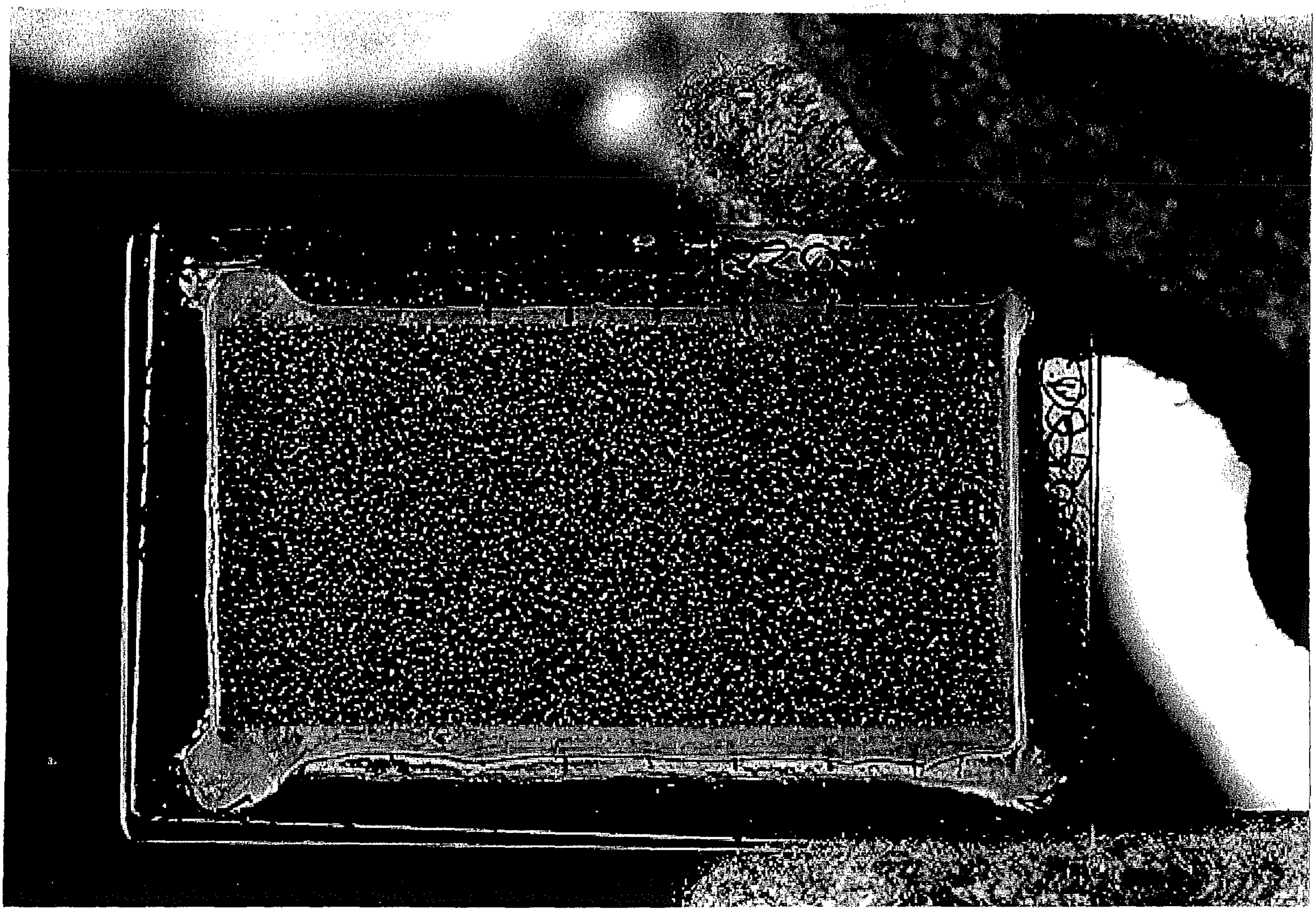
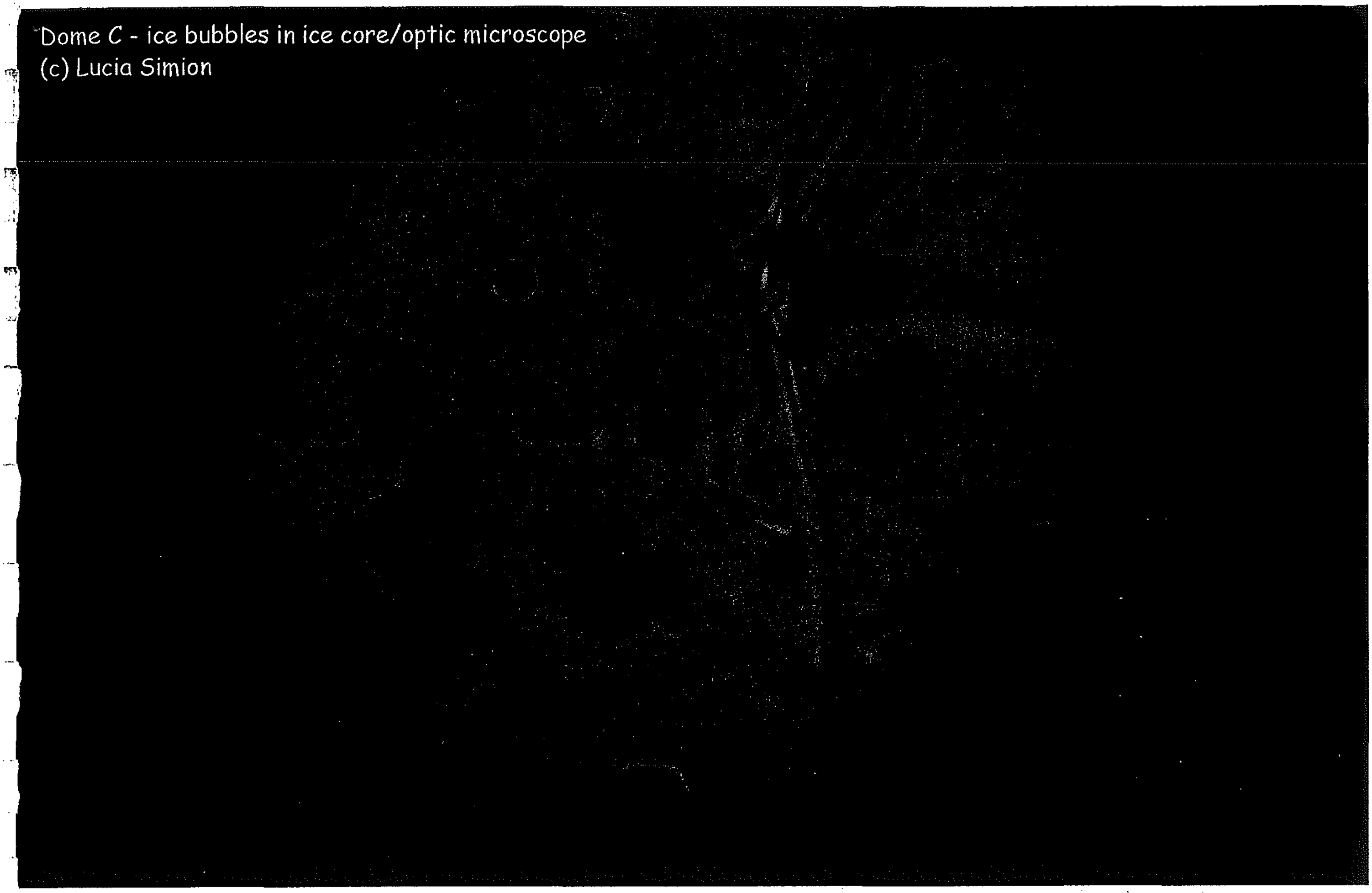
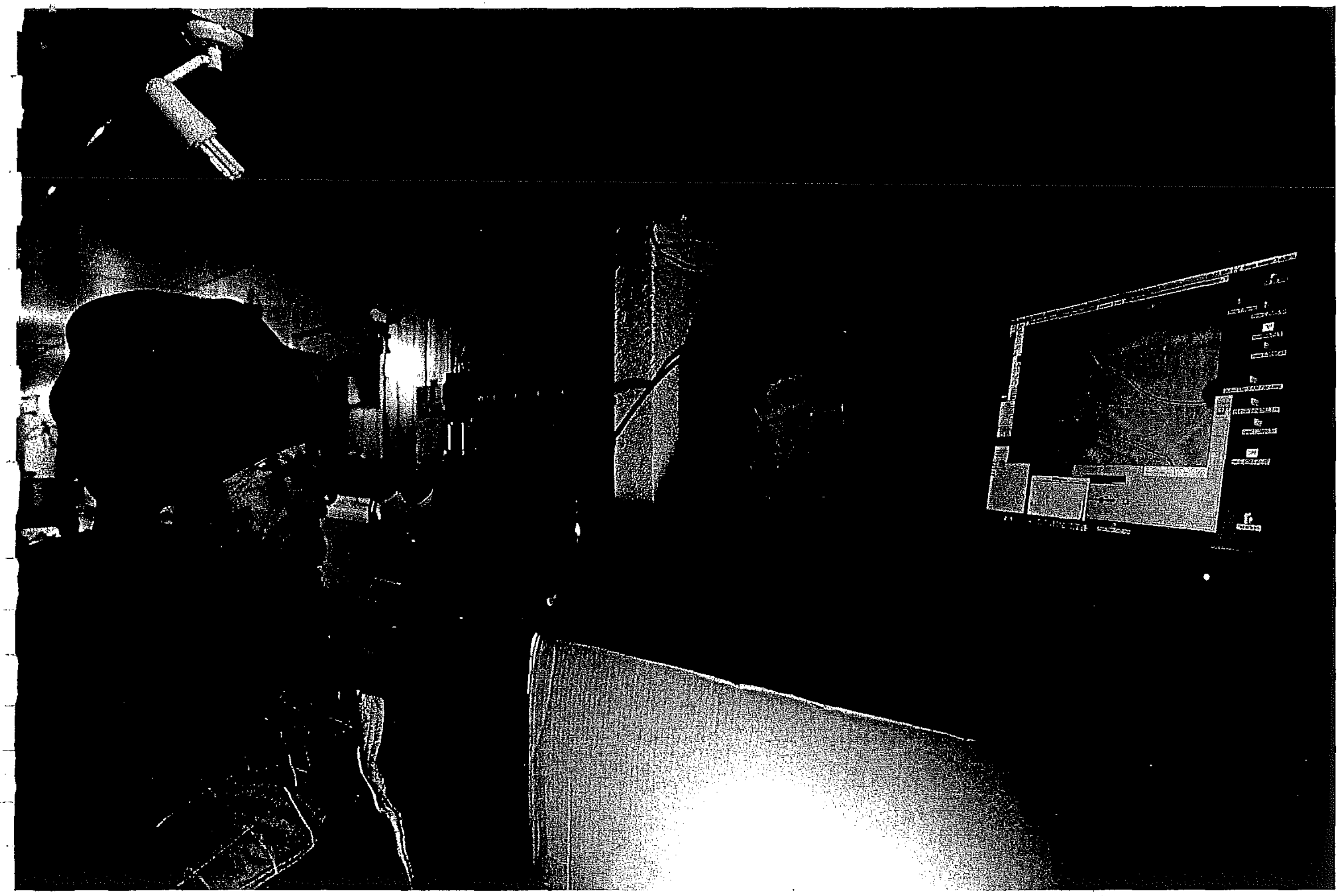


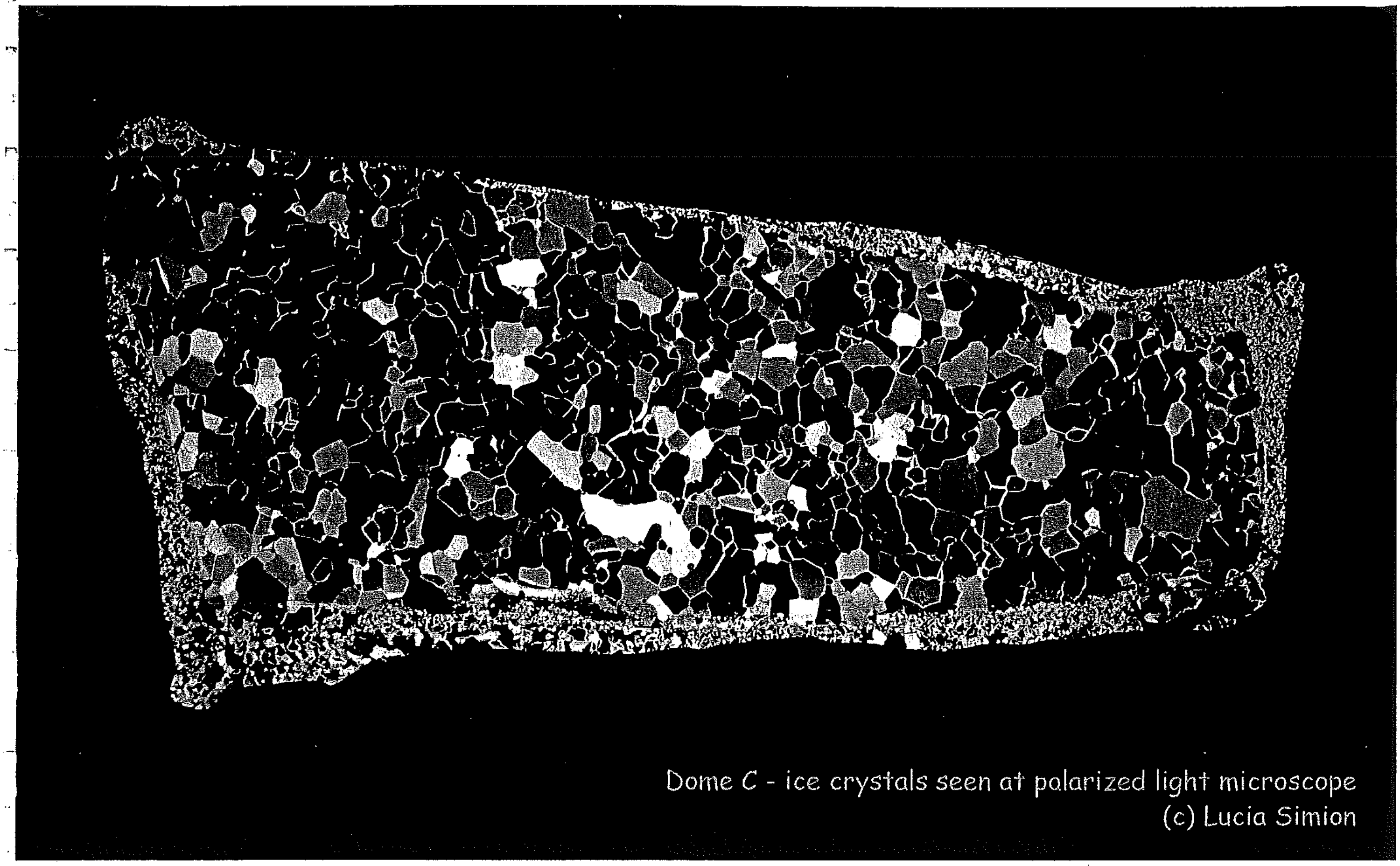
Dome C: Air bubbles in a thin "slice of an ice core. Bubbles are still visible at naked eye because the ice core was extracted from a depht of 800 metres. Below 1.000 metres the atmospheric pressure is so high that the air molecules become highly instable and tend to form a compound with the ice crystals, named *chlathrate hydrate;* therefore below 1.000 m the bubbles are no longer visible at naked eye. Bubbles dimensions range between 20 and 300 microns; the largest have a diameter of 1 millimetre. In the Antarctic ice there are 1.000 air bubbles per cube centimetre. **Ph. Lucia Simion**



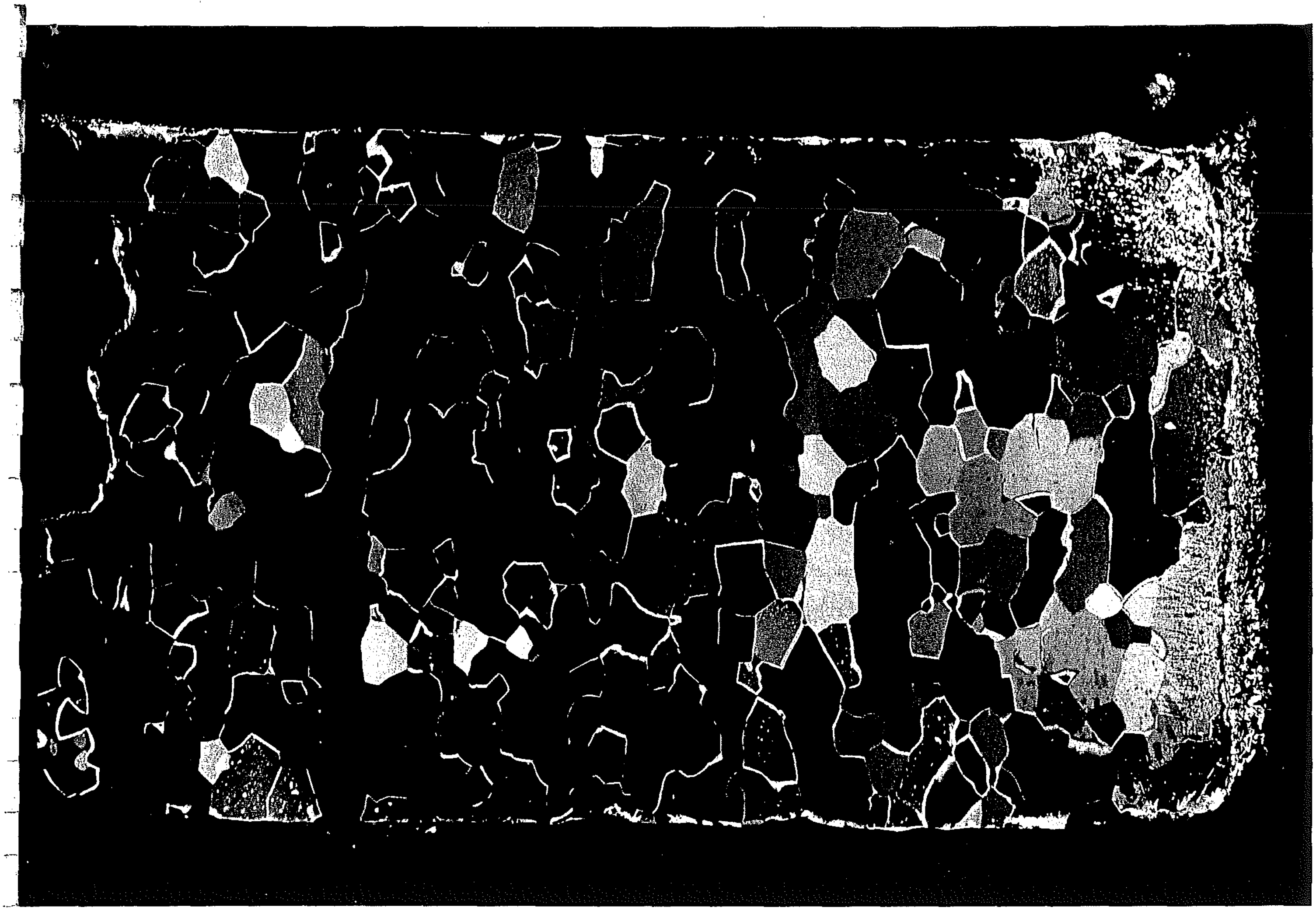
Dome C: Air bubbles in a thin "slice of an ice core, seen at the optical microscope. Bubbles are still visible because the ice core was extracted from a depht of 800 metres. Below 1.000 metres the atmospheric pressure is so high that the air molecules become highly instable and tend to form a compound with the ice crystals, named *chlathrate hydrate;* therefore below 1.000 m the bubbles are no longer visible at naked eye. Bubbles dimensions range between 20 and 300 microns; the largest have a diameter of 1 millimetre. In the Antarctic ice there are 1.000 air bubbles per cube centimetre. **Ph. Lucia Simion**



Dome C: German glaciologist Sepp Kipfsthul (AWI) observes the shape and dimensions of tiny air bubbles included in the ice, as they are magnified by a microscope and shown on a screen. **Ph. Lucia Simion**



Dome C: Ice crystals shape and dimensions seen at the polaryzed light. The crystals grow larger and larger with the increasing depht. **Ph. Lucia Simion**



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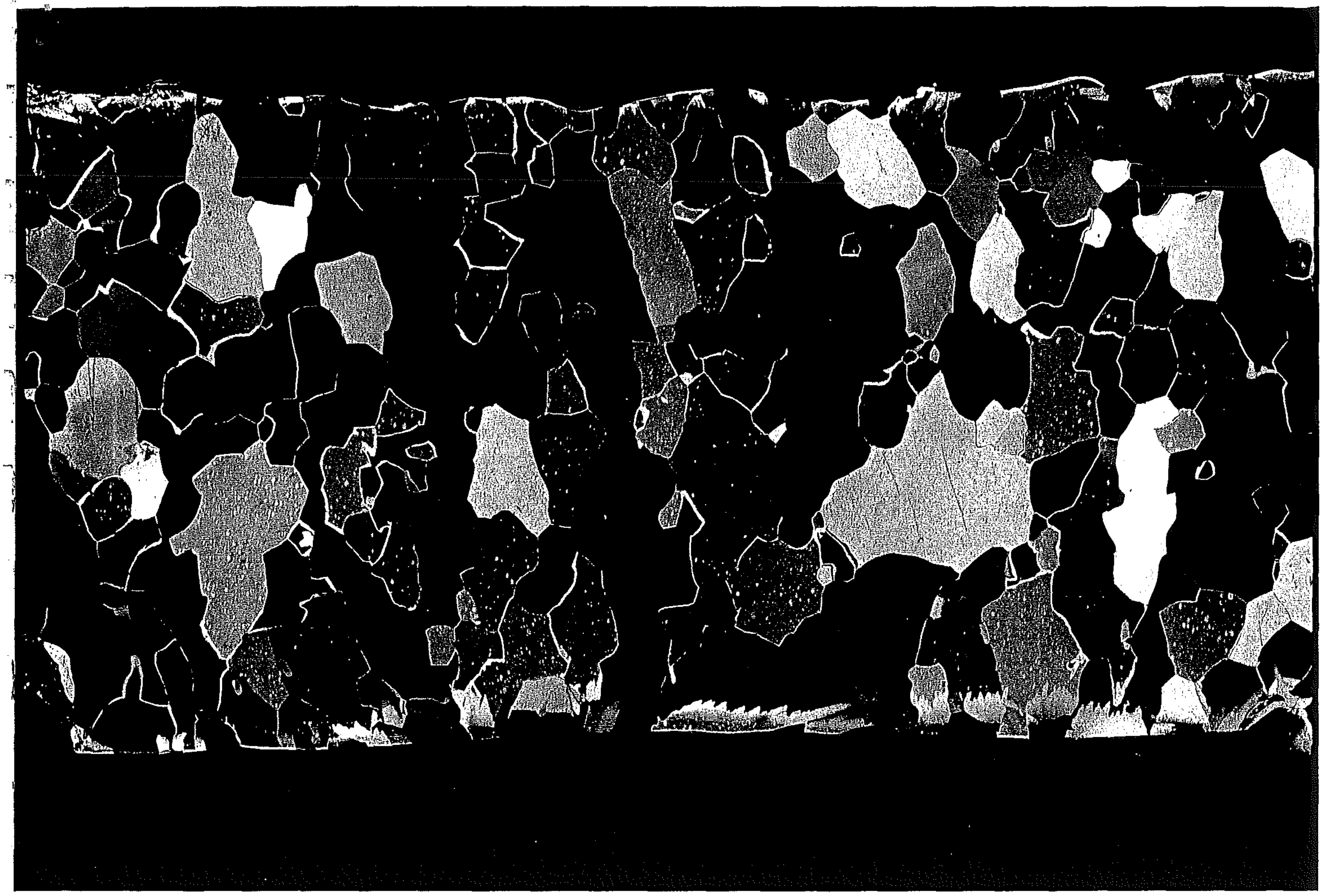
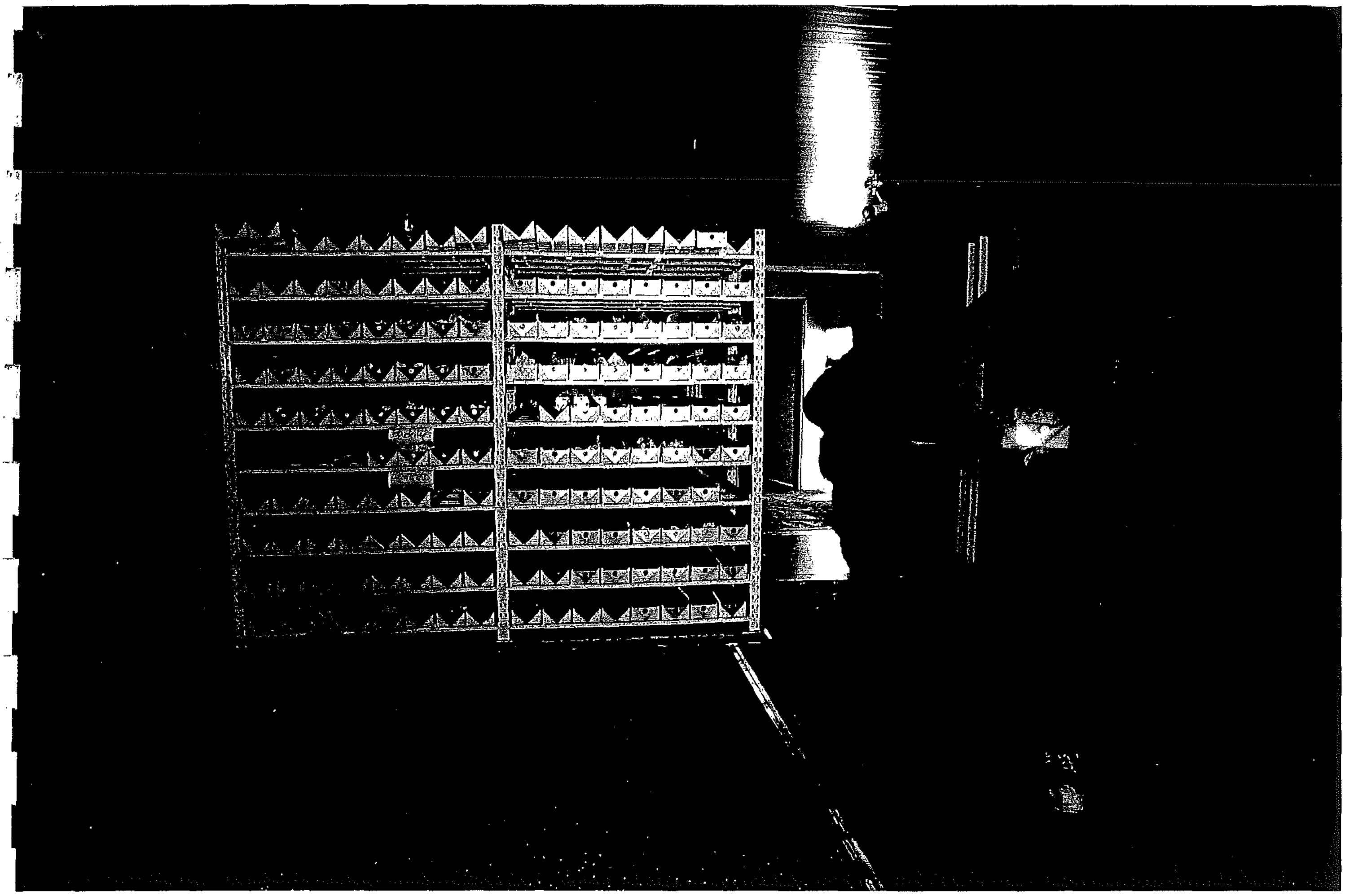
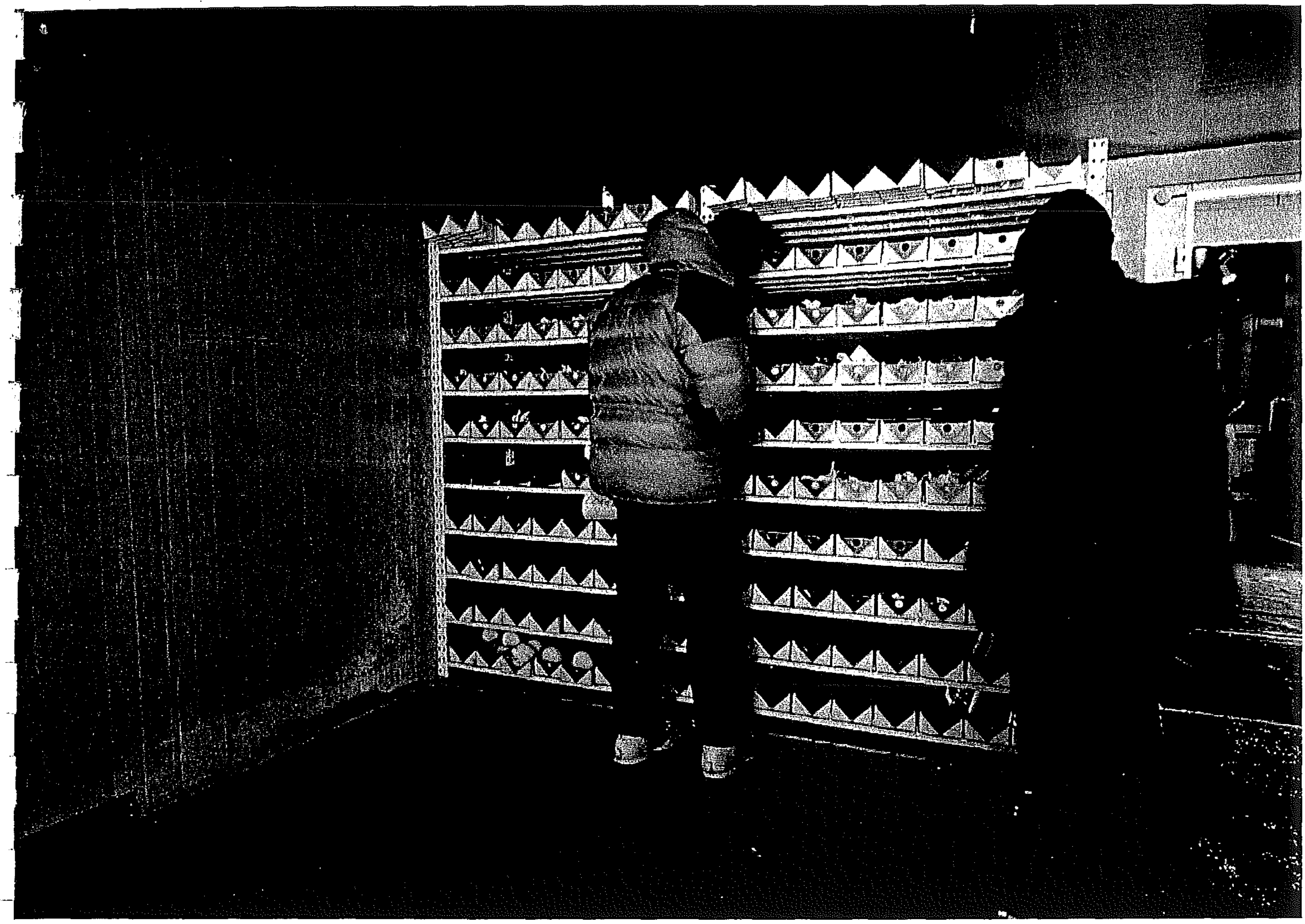
Ph. Lucia Simion



Dome C: Ice crystals shape and dimensions seen at the polaryzed light. The crystals grow larger and larger with the increasing depht.
Ph. Lucia Simion



Dome C: the "buffer room", where the ice cores are stocked prior to being examined by the glaciologists. **Ph. Lucia Simion**



Eight glacial cycles from an Antarctic ice core

The first analysis of the deep ice core from Dome C were published in the journal Nature dated June 10, 2004 (*Eight glacial cycles from an Antarctic ice core*). These results provides a climate record for the past 740,000 years. For the four most recent glacial cycles, the data agree well with the record from Vostok (420.000 years).

The earlier period, between 740,000 and 430,000 years ago, was characterized by less pronounced warmth in interglacial periods in Antarctica, but a higher proportion of each cycle was spent in the warm mode.

The transition from glacial to interglacial conditions about 430,000 years ago (Termination V) resembles the transition into the present interglacial period in terms of the magnitude of change in temperatures and greenhouse gases, but there are significant differences in the patterns of change. The interglacial stage following Termination V was exceptionally long—28,000 years compared to, for example, the 12,000 years recorded so far in the present interglacial period. Given the similarities between this earlier warmperiod and today, our results may imply that *without human intervention*, a climate similar to the present one would extend well into the future.

The first results confirm that over the last 740,000 years the Earth experienced eight ice ages, when Earth's climate was much colder than today, and eight warmer periods (interglacials). In the last 400,000 years the warm periods have had a temperature similar to that of today. Before that time they were less warm, but lasted longer. By comparing the pattern of this past climate with global environmental conditions today the EPICA team conclude that, without human influence, we could expect the present warm period to last at least another 15 000 years.

The next step in the research is to extract air from tiny bubbles in the ice, and to find out how the atmosphere's composition has varied. Preliminary analyses show that the present carbon dioxide concentration is the highest level seen in the last 440,000 years. By understanding what drove past changes in climate, the scientists expect to improve predictions about future climate.

The Dome C drilling is part of the 'European Project for Ice Coring in Antarctica' (EPICA). The team at Dome C endured summer temperatures as low as minus 40°C at the remote drilling site over a thousand kilometres from the nearest research station.

"It's very exciting to see ice that fell as snow three-quarters of a million years ago" - says Dr Eric Wolff, from British Antarctic Survey -"These results tell us that we won't have an ice age any time soon. However, we may have a heat wave if we are unable to control CO_2 emissions and other greenhouse gases entering the atmosphere. Our next step is to investigate CO_2 in the ice cores and by understanding what has driven the natural changes seen in the ice record, we will create better models to predict how climate might change in the future."

The EPICA research team is using the unique climate record from ice cores to investigate the relationship between the chemistry of the atmosphere and climate changes over the past 740,000 years, especially the effects of carbon dioxide, methane and other components of the atmosphere. The results will be used to test and enhance computer models used to predict future climate.

The ice cores are cylinders of ice 10 cm in diameter that are brought to the surface in lengths of about 3 metres at a time. Snowflakes collect particles from the atmosphere, and pockets of air become trapped between snow crystals as ice is formed. Analysis of the chemical composition and physical properties of the snow and the trapped air, including atmospheric gases such as CO_2 and methane, shows how the Earth's climate has changed over time.

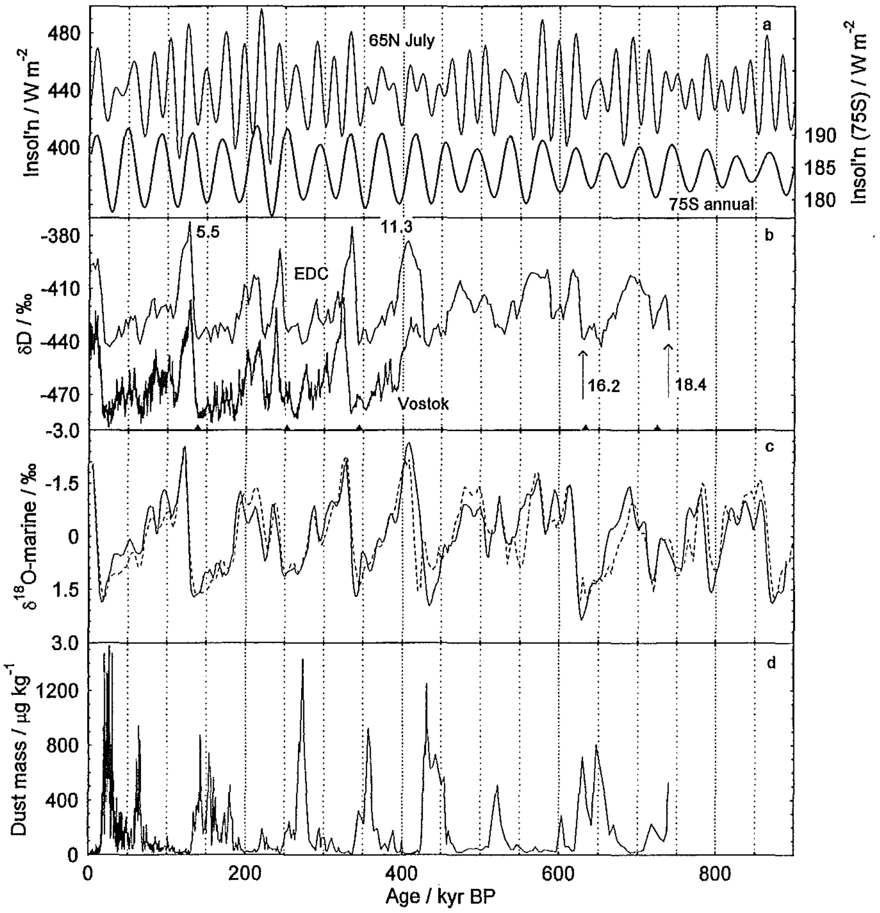


Figure 2: Comparison of EPICA Dome C data with other palaeoclimatic records. a, Insolation records 4. Upper blue curve (left axis), mid-July insolation at 658 N; lower black curve (right axis), annual mean insolation at 758S, the latitude of Dome C. b, dD from EPICA Dome C (3,000-yr averages). Vostok dD (red) is shown for comparison 1 and some MIS stage numbers are indicated; the locations of the control windows (below 800-m depth) used to make the timescale are shown as diamonds on the x axis. c, Marine oxygen isotope record. The solid blue line is the tuned low-latitude stack of site MD900963 and ODP677 3; to indicate the uncertainties in the marine records we also show (dashed red line) another record, which is a stack of seven sites for the last 400 kyr but consisting only of ODP site 677 for the earlier period 2. Both records have been normalized to their long-term average. d, Dust from EPICA Dome C.

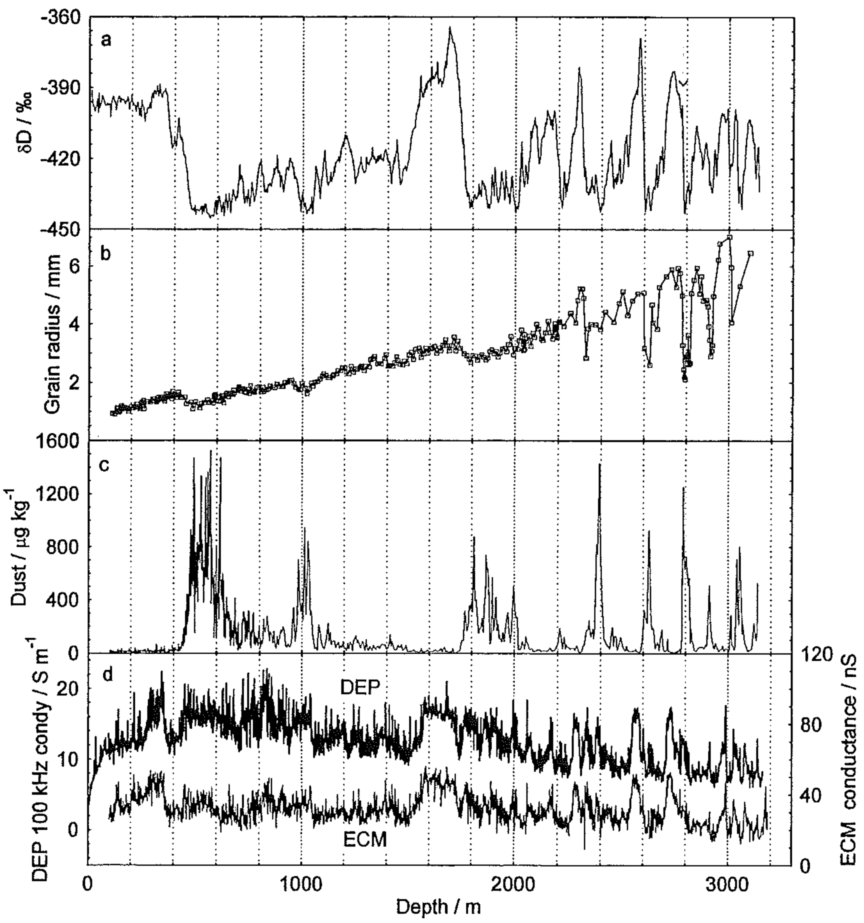


Figure 1: Measured parameters from the EPICA Dome C ice core, on an ice depth scale. **a**, dD, averaged over 3.85-m sections. **b**, Grain radius, measured approximately every 10 m. **c**, Dust concentration—below 787 m, there is one sample every 5.5 m; above that, one sample every 1.5 m. **d**, Electrical data (as discussed in the Methods), in 1-m averages. Termination V is marked by an arrow in **a**.

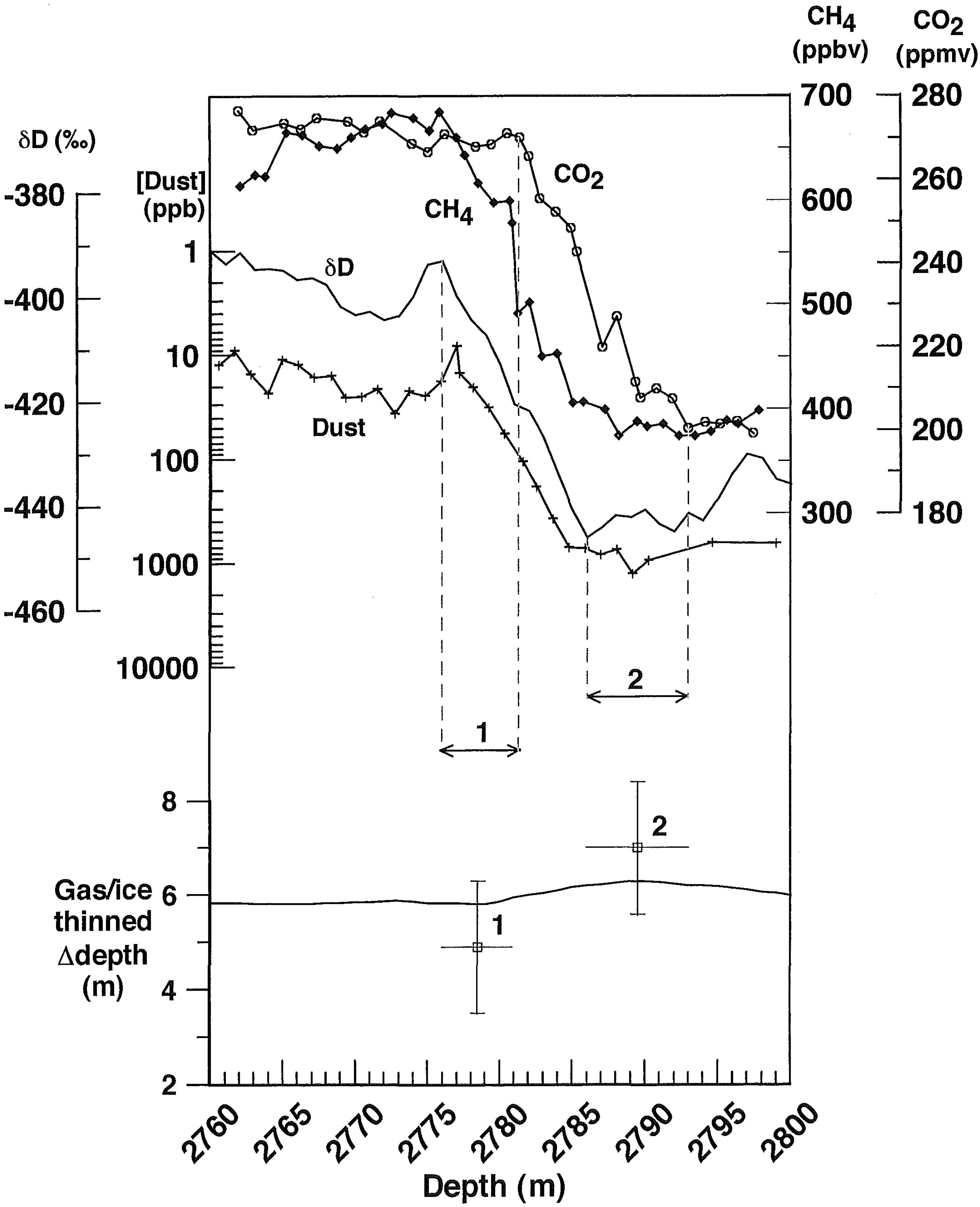


Figure 3 Termination V in the EPICA Dome C ice core on an ice depth scale. The top panel shows the ice-core parameters: circles, CO2; diamonds, CH4; line with no symbols, dD; crosses, dust. The lower panel shows the modelled difference in depth between ice and air of the same age (line) along with estimates of the actual difference (error bars are based on uncertainty in aligning common events) for events considered roughly contemporaneous on the basis of their behaviour in later terminations at Vostok. Event 1, CO2 peak/dD peak; event 2, CO2 early increase/dD early increase.

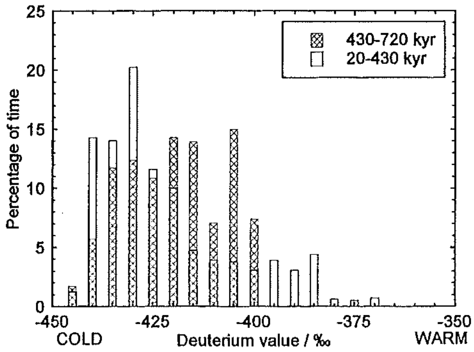


Figure 4 Histogram of dD values before and after 430 kyr. The bars show the occurrence of values within 5‰ windows for each of the periods, indicating that for the earlier period, there are no very warm values, but the time spent in warm and cold periods is more even than in the later period.

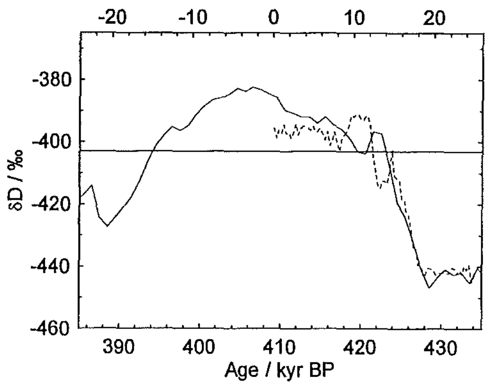


Figure 5 Comparison of Termination V plus MIS 11 with Termination I plus Holocene. dD data for MIS 11 (1-kyr averages) are shown as a solid blue line using the lower x axis; data for the Holocene are shown as a dashed red line using the upper x axis. Various alignments could be made, but we have adjusted the x axes so that the start of each termination is aligned. A horizontal line is drawn at 2403‰.

Eight glacial cycles from an Antarctic ice core

EPICA community members*

A full list of authors appears at the end of the paper

The Antarctic Vostok ice core provided compelling evidence of the nature of climate, and of climate feedbacks, over the past 420,000 years. Marine records suggest that the amplitude of climate variability was smaller before that time, but such records are often poorly resolved. Moreover, it is not possible to infer the abundance of greenhouse gases in the atmosphere from marine records. Here we report the recovery of a deep ice core from Dome C, Antarctica, that provides a climate record for the past 740,000 years. For the four most recent glacial cycles, the data agree well with the record from Vostok. The earlier period, between 740,000 and 430,000 years ago, was characterized by less pronounced warmth in interglacial periods in Antarctica, but a higher proportion of each cycle was spent in the warm mode. The transition from glacial to interglacial conditions about 430,000 years ago (Termination V) resembles the transition into the present interglacial period in terms of the magnitude of change in temperatures and greenhouse gases, but there are significant differences in the patterns of change. The interglacial stage following Termination V was exceptionally long—28,000 years compared to, for example, the 12,000 years recorded so far in the present interglacial period. Given the similarities between this earlier warm period and today, our results may imply that without human intervention, a climate similar to the present one would extend well into the future.

The climate of the last 500,000 years (500 kyr) was characterized by extremely strong 100-kyr cyclicity, as seen particularly in ice-core[1] and marine-sediment[2,3] records. During the earlier part of the Quaternary (before 1 million years ago; 1 Myr BP), cycles of 41 kyr dominated. The period in between shows intermediate behaviour, with marine records showing both frequencies and a lower amplitude of the climate signal[2,3]. The observed frequencies arise from parameters of the Earth's orbit that control the amount, and the seasonal and latitudinal distribution, of solar radiation[4]. However, the reasons for the dominance of the 100-kyr (eccentricity) over the 41-kyr (obliquity) band in the later part of the record, and the amplifiers that allow small changes in radiation to cause large changes in global climate, are not well understood. New records of the earlier periods, looking at parameters unavailable in marine records, are needed.

Ice cores provide the most direct and highly resolved records of (especially) atmospheric parameters over these timescales. They record climate signals, as well as forcing factors of global significance such as greenhouse gases and of more regional significance such as atmospheric aerosol content. Until now, ice-core data have been available only for the past 420 kyr, with the longest record coming from Vostok in East Antarctica[1], supported by the 340-kyr record from Dome Fuji[5]. These data indicated the similarities of the last four glacial terminations. They showed that glacials and interglacials had similar bounds in the measured properties over the last four cycles. Most tellingly, they showed the very close association between greenhouse gases[1,6] (CO_2, CH_4) and climate (as recorded using the Antarctic temperature proxy, the deuterium/hydrogen ratio in ice, represented as δD) over this period. The Vostok record has become a compelling target against which other records and modelling efforts are tested.

The European Project for Ice Coring in Antarctica (EPICA) is a consortium of laboratories and Antarctic logistics operators from ten nations, with the goal of obtaining two deep ice cores in East Antarctica. The study of one core, from Kohnen Station in the Dronning Maud Land sector of Antarctica (see Supplementary Fig. 1) is aimed at producing a high-resolution record of at least one glacial–interglacial cycle in the sector of Antarctica facing the Atlantic Ocean, for comparison with Greenland records[7]. The second core (named EDC) from Dome C (75° 06′ S, 123° 21′ E, altitude 3,233 m above sea level), discussed here, is aimed at producing a record of the longest time period possible. The site[8] has an ice thickness of 3,309 ± 22 m; the current drilling depth is 3,190 m, of which 3,139 m has been analysed for a wide range of constituents. The current mean annual surface temperature is $-54.5\,°C$, and the snow accumulation rate is $25\,kg\,m^{-2}\,yr^{-1}$ (2.5 cm water equivalent per year). The drill site is 56 km from the site of a previous Dome C core[9] that provided records extending into the last glacial period, and 560 km from the site of the Vostok cores[1]. The completion of the Dome C core was delayed when the first drilling became stuck at 788 m in 1999, and this shorter EDC96 core has already yielded many important results from the last 45 kyr (see, for example, refs 10–14).

Here we present the EDC records of δD and other parameters, analysed at low resolution, for the available core. We show that the core represents 740 kyr, including all of marine isotope stage (MIS) 11, which was not completed in the Vostok record, and running through a further three complete 100-kyr cycles, to MIS 18.4. We compare the amplitude and frequency structure of the period before MIS 11 with that of the more recent period. We focus in more detail, with new greenhouse-gas and ice-chemical data, on Termination V, from MIS 12 to MIS 11, discussing first the integrity of the record. The different parameters measured on this termination are then discussed in terms of similarities to and differences from younger terminations.

Stratigraphy of the EDC core

The ice-core data (see Methods) are reported in Fig. 1 as a function of depth. In this section, conductivity, grain size, dust and δD data, taken together, allow us to define a reliable stratigraphy of the core in terms of terminations and of broad correspondence with the deep-sea record. In the following section, we derive a timescale—which should be considered preliminary—and develop arguments supporting our claim that the core stratigraphy is undisturbed at the current depth (3,139 m) despite the relative proximity of the bedrock (less than 200 m).

Under the conditions at Dome C, both measurements (see Methods) of electrical conductivity[15] are dominated by variations in the acidity of the ice[16]. This property does not vary in a simple way with climate, increasing in both very cold and very warm stages, with the lowest values in intermediate climates. Cold periods in Antarctica are characterized by much greater dust fallout than is found during interglacials (for example, the Last Glacial Maximum (LGM)/Holocene ratio of 26 for dust flux[13]), related to a combination of increased aridity and wind strength. Large numbers of dust particles within the ice lead to a decrease in the ice-grain growth rate[17]. Consequently, each significant decrease of the average grain radius (Fig. 1) also marks an interglacial to glacial transition. The isotopic composition of the ice, δ*D* (used here) and $\delta^{18}O$, is classically used as an indicator of temperature change. Isotopic models predict that δ values should vary linearly with temperature in mid- and high latitudes. There is now a series of arguments supporting the use of this present-day temperature/isotope spatial slope to interpret isotopic records from Antarctica[18,19], at least for deep ice cores from the East Antarctic plateau.

Electrical, dust and δ*D* (Fig. 2) data can easily be matched between the EDC and Vostok cores into stage 11. We deduce that ice from 3,310 m at Vostok and from ~2,770 m at EDC corresponds to the same time period (423 kyr BP in the GT4 Vostok chronology). Transition V is then very clearly marked both in the dust, grain size and δ*D* records with the coldest part of MIS 12 at around ~2,790 m (Fig. 1), and with Termination V (that is, the MIS 12 to MIS 11 transition) roughly corresponding to the depth interval between 2,790 and 2,760 m.

Below the dielectric-profiling peak corresponding to MIS 11 there is a large depth interval with low dielectric-profiling values. There is, however, a clear dust peak, as well as a large decrease in the average grain size, at a depth of 2,910 m, which should correspond to the cold MIS 14, thus implying that there is no dielectric-profiling peak within MIS 13. The δ*D* record confirms that the interglacial MIS 13 peaks at a depth of 2,842 m, but is considerably colder than subsequent interglacials. This intermediate climate is insufficient to give a dielectric-profiling peak, probably because of reduced preservation of volatile acids[20].

From the δ*D* record, we first note a clear change in the amplitude of glacial–interglacial changes before and after MIS 12, with the older period being characterized by just one minimum as deep as those observed during the last 400 kyr, and by consistently lower maxima (by about 20‰). As discussed below, this change of amplitude corresponds to the mid-Brunhes climate shift (and does not result from some smoothing process in the ice). There is an excellent correspondence between the δ*D* and the dust record and based on these we can assign the base of the transition at ~3,042 m to the next cold stage, MIS 16.2. In the deep-sea core record, stage 16.2 corresponds to particularly low sea level and was probably very cold. This is exactly what is seen in the δ*D* where, before MIS 12, only stage 16 reached δ*D* levels as low as those of the LGM. The next δ*D* peaks (low dust) can then be attributed to full interglacial 17 and interstadial 18.3 with the bottom of the record corresponding to MIS 18.4.

Timescale and integrity of the deep ice

The timescale (called EDC2; see Methods) developed for the Dome C deep ice core is based on an inverse dating method[21], constrained by a small number of control age windows, which are mainly set to glacial terminations by comparison to the marine records. The fact that a simple one-dimensional model with only four free parameters can be matched (to 3,139 m depth) so well, in both timing and shape, with the orbitally tuned marine records (Fig. 2c) is evidence for the integrity of the stratigraphy of the Dome C record. The good match extends through the period from 338 to 626 kyr, in which there are no imposed control windows. The difference between the ages of gas bubbles and the surrounding ice was computed with a firn model[22].

The first section of EDC ice that is novel, that is, older than was

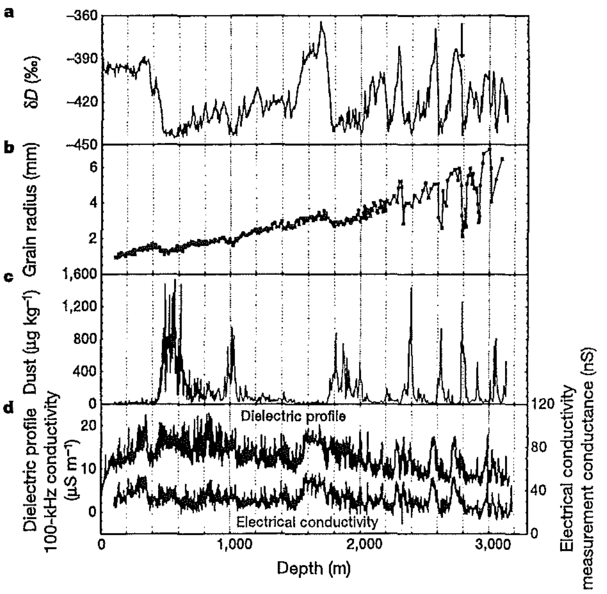


Figure 1 Measured parameters from the EPICA Dome C ice core, on an ice depth scale. **a**, δ*D*, averaged over 3.85-m sections. **b**, Grain radius, measured approximately every 10 m. **c**, Dust concentration—below 787 m, there is one sample every 5.5 m; above that, one sample every 1.5 m. **d**, Electrical data (as discussed in the Methods), in 1-m averages. Termination V is marked by an arrow in **a**.

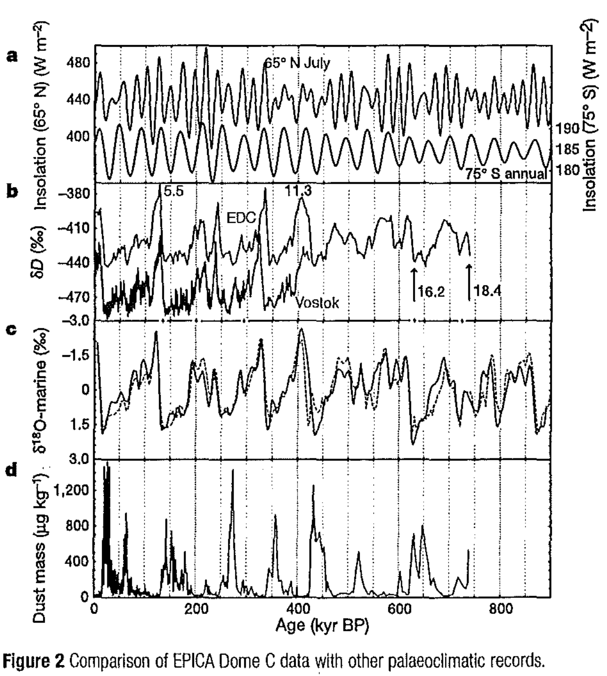


Figure 2 Comparison of EPICA Dome C data with other palaeoclimatic records. **a**, Insolation records[4]. Upper blue curve (left axis), mid-July insolation at 65° N; lower black curve (right axis), annual mean insolation at 75°S, the latitude of Dome C. **b**, δ*D* from EPICA Dome C (3,000-yr averages). Vostok δ*D* (red) is shown for comparison[1] and some MIS stage numbers are indicated; the locations of the control windows (below 800-m depth) used to make the timescale are shown as diamonds on the *x* axis. **c**, Marine oxygen isotope record. The solid blue line is the tuned low-latitude stack of site MD900963 and ODP677[3]; to indicate the uncertainties in the marine records we also show (dashed red line) another record, which is a stack of seven sites for the last 400 kyr but consisting only of ODP site 677 for the earlier period[2]. Both records have been normalized to their long-term average. **d**, Dust from EPICA Dome C.

obtained at Vostok, is that of Termination V. The integrity of this section can be tested using the depth difference expected between contemporaneous events recorded in the gas and the solid phase. We measured CO_2 and CH_4 mixing ratios in the air enclosed in the ice at ~1-m resolution between 2,760 and 2,800 m (Fig. 3). From the Vostok findings over the last four terminations[23], we expect the following pairs of events to be roughly synchronous: (1) the CO_2 peak/δD peak, (2) the start of CO_2 increase/start of δD increase. The depth offset (Δdepth) values for these two pairs of 5 to 7 m are in reasonable agreement with Δdepth values calculated with the firn densification model, taking into account the thinning function obtained with the ice-flow model (Fig. 3). These observations support the conclusion that this part of the Dome C record is undisturbed, that is, that there is no folding of the ice.

Although visible ash layers tilted by a few degrees from the horizontal have been observed in the deeper ice, so far we have observed none of the highly inclined layers and overturned folds that were associated with stratigraphic disturbance in the lowest 10% of the deep Greenland (Summit) ice cores. The electrical records to 3,190 m also show no unexpectedly rapid changes, of the kind that might be diagnostic of folding. In conclusion, all the evidence supports the integrity of the ice-core stratigraphy to 3139 m.

Antarctic climate beyond MIS 11

One of the paradoxes of Quaternary climate is the dominance of 100-kyr periodicity in the past few climatic cycles, even though the amplitude of insolation changes at this period is rather small. This can be addressed by examining changes in the amplitude and frequency of climate through the Quaternary period. On the basis mainly of ice-volume records, two major transitions have been identified. The mid-Pleistocene revolution (MPR) is characterized by an increase in mean global ice volume, and a change in the dominant period from 41 to 100 kyr (ref. 2). Its timing is often considered to be at about 900 kyr BP (that is, before the scope of this paper). A second distinct climate change, the mid-Brunhes event (MBE, for example[24]), roughly corresponds to the transition between stage 12 and stage 11 (Termination V) about 430 kyr ago. The MBE is characterized by a further increase of ice-volume variations with, from then to the present day, four large-amplitude 100-kyr-dominated glacial–interglacial cycles. The intermediate period between the MPR and the MBE is characterized by a less-clear pattern. This schematic description of Quaternary climate, largely based on deep-sea isotopic records of ice-volume changes, also holds for at least some sea surface temperature records. For example, a composite South Atlantic 1,830-kyr record[25] shows cold and relatively stable summer temperatures before the MPR followed by higher-amplitude fluctuations between the MPR and the MBE and much stronger variations thereafter. Now we have the opportunity to examine the pre-MBE signal in Antarctic temperature and dust.

In the EDC δD record (Fig. 2), as in the marine-isotope records, the most striking feature is the greater amplitude of glacial–interglacial change in the period after Termination V (with 430 kyr as the boundary), compared to the earlier period. The standard deviation of the signals increases by 45% for EDC and 12% for the $\delta^{18}O$ record of ref. 3; other planktonic series show a similar feature[24]. The Devil's Hole calcite isotopic record[26], which, however, extends only back to 565 kyr BP, also shows less variability before than after the MBE and indeed resembles the EDC record over the part common to both records. In detail, the period before Termination V in EDC is characterized by somewhat less cold glacial maxima (with the exception of stage 16.2), but by very significantly less warm interglacials (Fig. 4). Less extreme (weaker amplitude) interglacials occupied a larger proportion of each glacial/interglacial cycle, with the result that the mean δD value before and after 430 kyr is quite similar. The new ice-core data strongly emphasize the contrast in climate before and after the MBE.

The driving mechanisms for neither the MPR nor the MBE are as yet well understood. Some properties of the insolation curves have

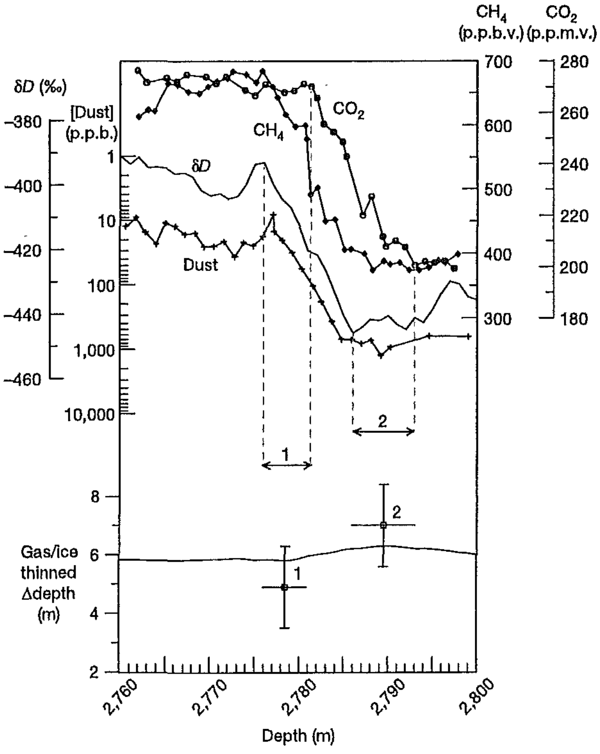


Figure 3 Termination V in the EPICA Dome C ice core on an ice depth scale. The top panel shows the ice-core parameters: circles, CO_2; diamonds, CH_4; line with no symbols, δD; crosses, dust. The lower panel shows the modelled difference in depth between ice and air of the same age (line) along with estimates of the actual difference (error bars are based on uncertainty in aligning common events) for events considered roughly contemporaneous on the basis of their behaviour in later terminations at Vostok. Event 1, CO_2 peak/δD peak; event 2, CO_2 early increase/δD early increase.

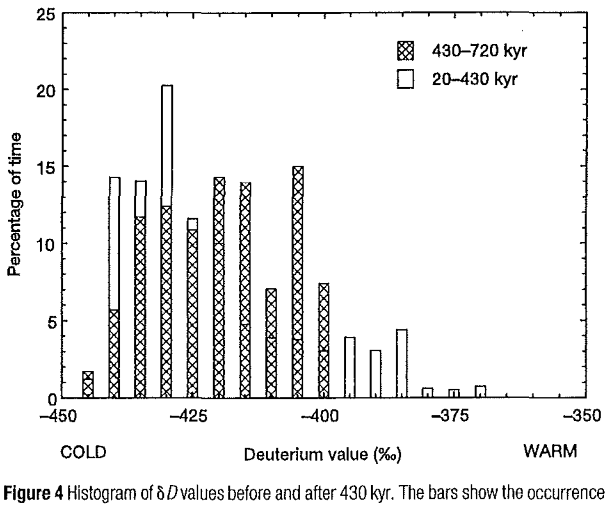


Figure 4 Histogram of δD values before and after 430 kyr. The bars show the occurrence of values within 5‰ windows for each of the periods, indicating that for the earlier period, there are no very warm values, but the time spent in warm and cold periods is more even than in the later period.

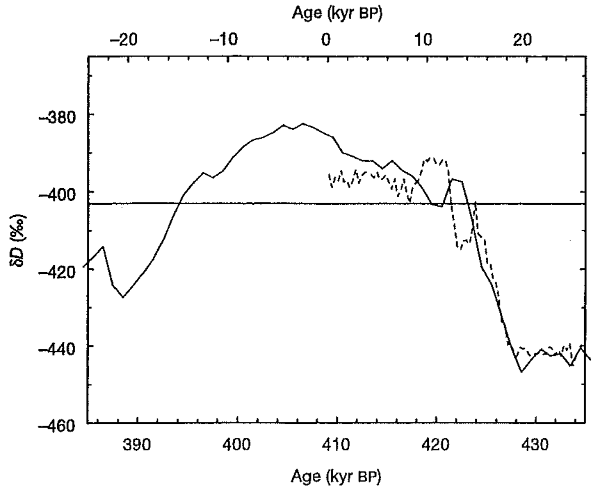


Figure 5 Comparison of Termination V plus MIS 11 with Termination I plus Holocene. δ*D* data for MIS 11 (1-kyr averages) are shown as a solid blue line using the lower *x* axis; data for the Holocene are shown as a dashed red line using the upper *x* axis. Various alignments could be made, but we have adjusted the *x* axes so that the start of each termination is aligned. A horizontal line is drawn at −403‰.

changed progressively over the last 800 kyr, with an increased amplitude of obliquity changes, for example, and therefore an increased variability of annual local insolation (Fig. 2a) in the later part of the record. However, none of the simple conceptual models developed to simulate the timing of the Pleistocene glaciations has been able to suggest an explanation of the MBE. The climate became more orderly and predictable after the MBE, perhaps as a result of the emergence of new feedback mechanisms linked with changes in boundary conditions, such as the strength of ocean circulation, albedo, carbon dioxide or isostasy[24]. At this stage, we have no additional clues allowing us to favour any one of these feedbacks, or to formulate other possibilities, but to obtain a detailed carbon dioxide record over 800,000 yr should certainly be helpful.

A final issue concerning the complete record is the stability in the size of the Antarctic ice sheet. Preliminary measurements of air content made between 2762.1 and 2783.0 m depth (MIS 11), between 3054.7 and 3059.1 m (MIS 16.3) and between 3099.8 and 3100.9 m (MIS 17.3) show the same mean value as that of EDC ice dating from the last 40 kyr (0.089 $cm^3 g^{-1}$). This suggests[27] that over the last 700 kyr, the surface elevation in this central part of East Antarctica has been as stable as during the last 40 kyr. This sets constraints, probably of the order of 5 m (ref. 28), on the possible contribution of this part of East Antarctica to changes in sea level[29].

Termination V

MIS 11 emerges as a key interglacial, both as viewed from the atmosphere in the EDC record and from the ocean in the $\delta^{18}O$ marine records. It delimits the frontier between two different patterns of climate, and has been identified as a unique and exceptionally long interglacial[30]. Some authors suggest that, because the orbital parameters (low eccentricity and consequently weak precessional forcing) are similar to those of the present and the next tens of thousands of years, MIS 11 may be the best analogue for present and future climate without human intervention[31]. In this context, we note (Fig. 5) that, on the EDC2 timescale, δ*D* (our temperature proxy) remains above −403‰ (the minimum 300-yr average value observed during the full Holocene epoch) for 28 kyr in MIS 11 (apart from a brief reversal near the start); in the Holocene, δ*D* has so far been above −403‰ for 12 kyr. The rate of change in δ*D* is very similar in Terminations V and I. Both terminations show a clear temperature reversal, but the one in the earlier period occurs after interglacial warmth has already been achieved. Thus the reversal at about 420 kyr might be seen as analogous to the Antarctic cold reversal (ACR) that occurred during Termination I at around 13 kyr, or it might be seen as similar to the dip (at about 8 kyr) that occurred after the early Holocene warm period.

Our low-resoluion data for CO_2, CH_4 (Fig. 3) and other parameters already provide information on how Termination V mimics or differs from younger terminations in terms of coupling between climate and greenhouse gases. With a minimum at 200 p.p.m.v. and 380 p.p.b.v. at the end of MIS 12 and a maximum at 275 p.p.m.v. and 680 p.p.b.v. at the start of MIS 11, CO_2 and CH_4 mixing ratios lie within the range observed during younger glacials and interglacials[1], the MIS 12 values being slightly at the higher end of the glacial range. These observations and the incomplete MIS 11 CO_2 record measured along the Vostok ice core[28] rule out unusual greenhouse conditions during MIS 11[32] or a link between coral-reef growth and the intense carbonate dissolution of MIS 11 through unusual CO_2 mixing ratios[30]. Other parameters measured on the core (Table 1), representing conditions and transport in different compartments of the environment, have very similar (glacial) values at equivalent points just before Terminations I and V and very similar (interglacial) values just after the two transitions. This confirms that, in all the proxies we are able to examine, there is no significant long-term trend in the period since the MBE.

The general shape of the greenhouse gas increases resembles younger terminations, that is, a regular trend for CO_2 and a two-step transition for CH_4 (slow increase followed by a rapid jump towards interglacial values); however, no Younger-Dryas-like event is observed in our CH_4 profile.

The most striking feature concerns the relative timing of the CO_2 and CH_4 increases compared with younger terminations: whereas CH_4 started to increase concomitantly with CO_2 (and Antarctic temperature) during the last four terminations, at Termination V it leaves its glacial background 4 to 5 kyr later than CO_2, by which time the latter had already increased by about 50 p.p.m.v. Similarly, the rapid jump of CH_4 punctuating the second part of its transition takes place when CO_2 approaches its maximum. Note that this is also the time when Antarctic temperature starts a slow decrease, that is, a typical expression of a bipolar see-saw as observed during stage 3 (ref. 33) and possibly Termination I[12]. Following its rapid jump at

Table 1 **Concentrations of major analytes measured along the EDC ice core**

Analytes	6–8 kyr BP (after Termination I)	20–22 kyr BP (before Termination I)	416–418 kyr BP (after Termination V)	430–432 kyr BP (before Termination V)
δ*D* (‰)	−399	−442	−395	−442
CO_2 (p.p.m.v.)	260	185	270	200
CH_4 (p.p.b.v.)	600	360	670	390
Dust (μg kg^{-1})	14	680	24	630
Na (μg kg^{-1})	20	101	23	99
SO_4^{2-} (μg kg^{-1})	92	201	98	216

Gas values are for Dome C. No corrections for interhemispheric differences or global averages have been applied. Data is shown for approximately equivalent periods before and after Terminations I and V.

the end of the termination, CH_4 continues to increase by ~100 p.p.b.v. for 2 to 3 kyr, another unusual feature when compared to the CH_4 trends during the early part of MIS 1, 5, 7 and 9 (ref. 1).

A thorough discussion of the causes of these greenhouse-gas peculiarities during Termination V is beyond the scope of this paper. But evidently the similarities and differences observed with younger terminations will stimulate the debate on how greenhouse gas and climate are coupled on Quaternary timescales.

Prospects from the rest of the core

In this paper, we have shown the extended climate record back to 740 kyr, and that the pattern of climate before MIS 11 was different to that which has followed for the past four glacial cycles. Although the results from MIS 11 indicate that without human intervention a climate similar to the present one would extend well into the future, the predicted increases in greenhouse-gas concentrations make this unlikely[34].

According to our preliminary timescale, extending the record to 3,190 m (ice already drilled but not analysed) will take the record back to 807 ± 10 kyr (MIS 20.2). The electrical records already obtained on this ice (Fig. 1), although difficult to interpret simply in terms of climate, certainly suggest that another glacial cycle will be found in this ice. This ice should include the Brunhes–Matuyama magnetic reversal, generally dated to about 780 kyr, and therefore give us the first indication of how a reversal is recorded in cosmogenic isotopes such as ^{10}Be.

There remains up to 120 m of ice still to drill. This will be difficult to obtain because the ice is near to the melting temperature. The timescale EDC2 extended to the base gives an age of 960 ± 20 kyr. Therefore, when the record is complete, we could expect to reach MIS 26 (just beyond the MPR), assuming that the integrity of the stratigraphy and all the approximations of the dating method are still reasonable down to the base. It will be of particular interest to see how the tight coupling between greenhouse gases and Antarctic temperature (δD) seen in the last 420 kyr evolves through the earlier parts of the record. □

Methods

Analysis

The electrical conductivity measurement determines the d.c. conductance between electrodes on a fresh ice surface. Dielectric profiling determines the conductivity of the ice at higher frequencies. Both were measured in the field at a temperature of −20 ± 2 °C, corrected[15,16] to −15 °C. Data were collected at high resolution and averaged to 1 m. Vertical thin sections were prepared in the field at a periodicity of 10 m, then digitized and analysed using an image analysis procedure[35] to determine the mean grain radius. A 3.4 cm × 3.4 cm strip of ice was melted on a hotplate in the field[36], and fed into various detectors. Aliquots (1.1-m averages) were also collected from this melting device into clean containers, frozen and shipped to Europe for ion chromatographic analysis[37] of major ions (presented for Termination V). All other measurements were made in laboratories in Europe after the ice had been shipped frozen from Dome C. δD was determined[10] on meltwater from 55-cm-long sections. This record, still discontinuous for some parts, should be considered as preliminary. Also, we used a 'quick' mode (each sample is measured twice instead of four times), leading to a typical accuracy of 1.5‰ (1σ), whereas we aim for a final precision of 0.5‰ over the entire core, as currently obtained for EDC96 (the upper 780 m). δD data shown in Fig. 1 correspond to values averaged across seven successive samples. The current precision and resolution are well adapted for the climatic interpretation discussed here (Fig. 2), in which we focus on the broad features of Antarctic climate changes over the past eight climatic cycles.

Dust concentration and size distribution was measured by a 256-channel Coulter Counter, set to register particles in the size range from 0.7–20 μm (ref. 13). In calculating mass concentrations, density was taken as 2,500 kg m^{-3}. CO_2 and CH_4 were measured (for Termination V) by a dry crushing[12] and a melt-refreezing extraction technique[38], respectively.

Models used for ice-core dating

Full details of the derivation of the timescale are given in the Supplementary Information. For the thinning rate computation, we used an ice-flow model[39], with prescribed surface elevation[40]. It has two poorly known parameters: the melting at the base of the ice sheet (F), which is the condition for the vertical velocity at the base, and a parameter (m) for the vertical velocity profile. The vertical strain rate is assumed to be proportional to $1-(z/H)^{(m+1)}$, where z is the depth and H is the ice thickness. The accumulation rate is deduced from the δD content of the ice, via the temperature of the inversion layer. This conversion involves two further tunable parameters. The last modelling step of the chronology is the evaluation of the difference between the gas age and the ice age (Δage), which is required to derive the age scale for the gas measurements. This is derived from a firn model[22]. The four poorly known parameters of the models are evaluated through the use of a small number of chronological controls, through a Monte Carlo inverse method[5,21]. The method searches for an optimal agreement, within the limits of the confidence interval of each assigned age (that is, we use control windows rather than control points) and using the same rules to define accumulation all along the record. In the top part of the core, we use the same control points as were used to derive the timescale (EDC1) recommended for the shallower part of the core[41]; EDC1 remains the recommended timescale for this part of the core, and hands over precisely to EDC2 at 800 m. For the bottom part of the core (that is, for the period older than 50 kyr), we used several age control windows derived by comparison to the stacked marine isotope curve of Bassinot[3], assuming a 4-kyr phase lag. These points are situated at Terminations II (1,738 m = 131 ± 6 kyr), III (2,311 m = 245 ± 6 kyr), IV (2,593 m = 338 ± 6 kyr), VII (3,038 m = 626 ± 6 kyr) and VIII (3,119 m = 717 ± 6 kyr). Note that the age of identical events in this EDC2 chronology can differ, over their common parts, from the Vostok and Dome Fuji chronologies, because of slightly different best-fit parameters in the model.

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Correspondence and requests for materials should be addressed to E.W. (ewwo@bas.ac.uk).

EPICA community members* (participants are listed alphabetically)

Laurent Augustin[1], Carlo Barbante[2], Piers R. F. Barnes[3], Jean Marc Barnola[1], Matthias Bigler[4], Emiliano Castellano[5], Olivier Cattani[6], Jerome Chappellaz[1], Dorthe Dahl-Jensen[7], Barbara Delmonte[1,8], Gabrielle Dreyfus[6], Gael Durand[1], Sonia Falourd[6], Hubertus Fischer[9], Jacqueline Flückiger[4], Margareta E. Hansson[10], Philippe Huybrechts[9], Gérard Jugie[11], Sigfus J. Johnsen[7], Jean Jouzel[6], Patrik Kaufmann[4], Josef Kipfstuhl[9], Fabrice Lambert[4], Vladimir Y. Lipenkov[12], Geneviève C. Littot[3], Antonio Longinelli[13], Reginald Lorrain[14], Valter Maggi[8], Valerie Masson-Delmotte[6], Heinz Miller[9], Robert Mulvaney[3], Johannes Oerlemans[15], Hans Oerter[9], Giuseppe Orombelli[8], Frederic Parrenin[1,6], David A. Peel[3], Jean-Robert Petit[1], Dominique Raynaud[1], Catherine Ritz[1], Urs Ruth[9], Jakob Schwander[4], Urs Siegenthaler[4], Roland Souchez[14], Bernhard Stauffer[4], Jorgen Peder Steffensen[7], Barbara Stenni[16], Thomas F. Stocker[4], Ignazio E. Tabacco[17], Roberto Udisti[5], Roderik S. W. van de Wal[15], Michiel van den Broeke[15], Jerome Weiss[1], Frank Wilhelms[9], Jan-Gunnar Winther[18], Eric W. Wolff[3] & Mario Zucchelli[19]*

1, Laboratoire de Glaciologie et Géophysique de l'Environnement (CNRS), BP 96, 38402 St Martin d'Hères Cedex, France; 2, Environmental Sciences Department, University of Venice, Calle Larga S. Marta, 2137, I-30123 Venice, Italy; 3, British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK; 4, Climate and Environmental Physics, Physics Institute, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland; 5, Department of Chemistry—Analytical Chemistry Section, Scientific Pole—University of Florence, Via della Lastruccia 3, 50019 Sesto Fiorentino (Florence), Italy; 6, Institut Pierre Simon Laplace/Laboratoire des Sciences du Climat et de l'Environnement, UMR CEA-CNRS 1572, CE Saclay, Orme des Merisiers, 91191 Gif-Sur-Yvette, France; 7, Niels Bohr Institute for Astronomy, Physics and Geophysics, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen, Denmark; 8, University of Milano-Bicocca, Dipartimento di Scienze Ambiente e Territorio, Piazza della Scienza 1, I-20126 Milan, Italy; 9, Alfred-Wegener-Institute for Polar- und Marine Research (AWI), Postfach 120161, D-27515 Bremerhaven, Germany; 10, Department of Physical Geography and Quaternary Geology, Stockholm University, S-106 91 Stockholm, Sweden; 11, Institut Polaire Français–Paul Emile Victor (IPEV), BP 75, 29280 Plouzane, France; 12, Arctic and Antarctic Research Institute, 38 Beringa Street, 199397 St Petersburg, Russia; 13, Department of Earth Sciences, University of Parma, Parco Area delle Scienze 157/A, I-43100 Parma, Italy; 14, Département des Sciences de la Terre et de l'Environnement, Faculté des Sciences, CP 160/03, Université Libre de Bruxelles, 50 avenue FD Roosevelt, B1050 Brussels, Belgium; 15, Institute for Marine and Atmospheric Research Utrecht (IMAU), Princetonplein 5, 3584 CC Utrecht, The Netherlands; 16, Department of Geological, Environmental and Marine Sciences, University of Trieste, Via E. Weiss 2, I-34127 Trieste, Italy; 17, Earth Science Department, University of Milan, Via Cicognara 7, 20129 Milano, Italy; 18, Norwegian Polar Institute, N-9296 Tromsø, Norway; 19, ENEA, CRE Casaccia, PO Box 2400, Via Anguillarese 301, 00060 S. Maria di Galleria (RM), Italy.

*Deceased.

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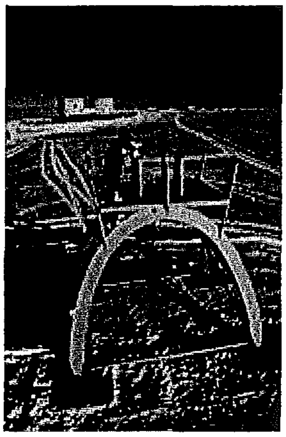
Dome C : Towering over and drilling deep

By Lucia S. Simion
Special to The Antarctic Sun

San Gimignano, the tiny Tuscan village built in the Middle Ages and world-famous for its stone towers, has a rival in the heart of the Antarctic.



A wooden platform at Dome C holds equipment to test the quality of data that can be gathered from the new station site. Photo by Lucia Simion//Special to The Antarctic Sun (See full-size image>>>)

The place is Dome C, the many-towered base run by the French and the Italian Antarctic programs on the East Antarctic plateau. It is quickly becoming an international research station, with scientists from the U.S., Britain, Denmark, Switzerland, French Algeria and Australia working there.

After the long polar night, when the temperatures dropped to -70°C, the tiny village was reinhabited Nov. 9. Plumes of smoke from the generator again heralded the presence of construction workers, ice drillers and glaciologists. Voices and skidoos animated the silent plateau and twice a day the base shook as a Caterpillar filled the snow melter to make water.

Compared to the 2001-2002 season, this field campaign was blessed with bright sun shining day and night over the plateau, a horizon of pure white all around and a delicate blue-sky overhead. In the evening hours, "diamond dust" often blew in on a gentle breeze.

The many towers

This season Dome C campsite looked almost like a "San Gimignano of the Antarctic," with towers, big and small, rising out of the flat landscape.

The largest are the ivory-and-coral colored twin buildings of the French-Italian Concordia station. After four years of construction, the new station will be ready to be occupied in a year, making it only the third year-round station on the plateau, along with Amundsen-Scott South Pole (U.S.) and Vostok (Russia).

By the end of December, both the "quiet" building, where the rooms and labs are located, and the "noisy" building, where the kitchen, dining room and storage rooms are, were sealed with panels. The "noisy" building was heated and a crew started working on the internal construction.

"The assembling of the ceilings of the noisy building are almost completed," said Serge Drapeau of the French Antarctic program and Concordia building manager, "and the internal subdivision as well. We are now ready to start mounting the ceilings in the second tower as well."

Drillers at Dome C examine some of their deepest and oldest ice cores yet, taken from 9,840 feet (3,000 meters). It is thought to contain ice at least 700,000 years old. Phot by Lucia Simion/Special to The Antarctic Sun (See full-size image>>>)

But completed or not, at 52-feet (16 m) high, the station towers are not the tallest at Dome C.

A much taller tower stands 2,624 feet (800 m) from Concordia. Its 105 feet (32 m) tall aluminum frame holds equipment to track the movements of the sun. Close-by there's a 20 foot (6-m) high aluminum tower with an instrument to validate the Atmospheric Infrared Sounder mounted on a NASA satellite, which passes over Dome C in its polar journey.

Last but not least, a wooden platform 20 feet (6 m) high designed by French architect Jean Dubourg was assembled in early December to hold the first of two 1-foot (30-cm) optical telescopes. The telescopes are part of a project to test the Dome C site by measuring the effect of the extremely stable air on the sharpness of a star.

The telescope has been monitoring the star Canopus for very long sequences, more than 300 hours altogether. It can focus on Canopus even during the very bright Antarctic daylight thanks to the exceptional transparency of the air at –30°C, the average temperature this season.

"The turbulence is even weaker than we expected," said Karim Agabi with the Department of Astrophysics at the University of Nice, which is leading the Concordiastro site-test project.

"Just looking (at) the star through the eyepiece is spectacular," said Agabi. "Nowhere else on Earth you can see such a stability and we now expect that it will be much better during the polar night."

During the first winter season many radiosoundings will be done to confirm the absence of turbulent winds at any altitude, said Agabi. The stellar image quality of the telescope focus will be tested during several months by means of three such telescopes working together in what is called a Generalized Seeing Monitor. A second identical platform will be assembled next season for a specific study of the bright star Alpha Centauri, which will be conducted by two independent telescopes.

Several other instruments are also assessing the quality of data that can be obtained from Dome C. Two of them will gather data for a full year at an automated laboratory set up by three Australian astronomers from the New South Wales University. The laboratory is called the AASTINO and looks like a "tomato hut," except the color is brilliant green.

Two experiments will sit on the AASTINO during 2003. One measures the transparency of the sky at sub-millimeter wavelength. The second is an acoustic radar that measures the turbulence in the lower atmosphere by bouncing pulses of sound from it. Both instruments have operated at South Pole for over a year and their operations at Dome C will provide important comparative data between the two sites.

In addition to the two AASTINO instruments, there are two other instruments that independently measure the amount of cloud cover at Dome C during the wintertime. In the future, additional site-testing instruments will be installed on the AASTINO.

Americans in polar Paris

Dome C is thus becoming one of the international stations of the Antarctic. The atmosphere is multicultural, friendly and cooperative and its French-Italian food is already famous from McMurdo to Dumont d'Urville. The location is considered exceptional for astrophysics and astronomy studies, for aeronomy research, glaciology, geomagnetism, climate study, seismology, search for micrometeorites and study of 14 subglacial lakes. The largest of the lakes is called "Concordia" and is surveyed by Italian geologist Ignazio Tabacco of the University of Milan.

During the 2002-2003 field season Dome C has been a sought-after place by scientists and technicians from the U.S., Britain, Denmark, Switzerland, French Algeria and Australia. Of course Italian and French make up the largest part of the population, which averages 50 to 60 people, since Dome C is their "polar hometown" on the plateau.

For the first time since the camp opened seven years ago, six Americans spent time at Dome C performing experiments, drilling ice cores or being part of the "Raid," the Caterpillar truck convoy bringing supplies to the station from Dumont d'Urville three times a year.

"They have a lot of experiential knowledge just from doing it so long," said Ralph Horak, one of two Americans who accompanied the 25-day, roundtrip supply traverse. Even on the long road trip, the culture of the traverse was apparent, Horak said. The French drivers drank wine with lunch and ate escargot for Christmas.

"They cooked them with a lot of garlic butter and I figure you cook anything with a lot of garlic butter you can eat it," said Horak, who gave the French delicacy a try, but said "I wouldn't order it at a restaurant."

Several of the Dome C towers were put up in collaboration with American researchers. The tallest tower holds a Cimel sun-photometer, the first to be used on the polar plateau. It is a joint effort of Richard Brandt with the atmospheric science department at the University of Washington in Seattle and Dephine Six, a French researcher with the Laboratoire de Glaciologie et de Géophisique de l'Environnement in Grenoble.

The sun-photometer is a portable and automatic tracking device, measuring sun and sky luminance to near infrared wavelengths. The instrument automatically computes the position of the sun and tracks its movements, which is useful for calibrating satellite borne-sensors.

Nearby, a much shorter tower houses an instrument, called the Polar Atmospheric Emitted Radiance Interferometer, which also is used to validate satellite instruments. The interferometer was built by Von P. Walden and Brad Halter of the University of Idaho in Moscow. They collaborated with Bob Stone from the Climate Monitoring and Diagnostic Laboratory at the NOAA in Boulder, Colo.

Drilling deep

Like a true European village, Dome C also has "The Cathedral" – in this case a large white tent that is the headquarters of the EPICA ice core drilling operations. The drilling operations had restarted in late November at the depth of 9,416 feet (2,871 m), with the goal of reaching the bedrock at 10,824 feet (3,300 m). It was there, about midday on Dec. 12, the drillers extracted an ice core from the depth of 9,849 feet (3,000 m). This 10-foot (3-m) section of core was dated using an electrical profiling technique as being 700,000 years old. In comparison, the ice core taken from over Lake Vostok goes deeper, to about (3,623 m), but contains a climate record going back about 400,000 years.

To witness such an extraordinary event, all the people of Dome C flocked inside The Cathedral, including Bill Mason with the Space Science and Engineering Center at the University of Wisconsin in Madison. Mason spent two months in Dome C as part of the team of eight drillers who contributed to the great success of EPICA in the 2002-2003 season.

In the days following the 3,000 meter mark, the drilling operations sped up and the depth of 10,168 feet (3,100 m) was easily reached. Then suddenly the ice refused to be drilled again, as if it was a living thing.

The Cathedral was desperately empty and silent, its door shut. No more drilling, no more cores, nothing. We were used to passing by from time to time and asking the drillers, "How's the ice core?" Usually they answered, "Brilliant, a nice core of three meters with huge ice crystals," but now all was over.

Many attempts were made to continue the drilling operations: the drilling device was changed, the blades as well, the speed of rotation was varied, etc. A test of the temperature, pression and inclination of the hole was made. Then drilling restarted successfully on December 23, to stop the following day.

Finally alcohol and a fiberglass tube for a reservoir were both provided by the Americans at McMurdo station and delivered by Twin Otter to Dome C. On Jan. 7 the drilling resumed using an alcohol solution and by Jan. 21 the drillers reached 10,398 feet (3,170 m), said EPICA Chief Driller Laurent Augustin, with the Laboratoire de Glaciologie et Géophisique de l'Environnement in Grenoble.

"We had to design and build a special heated reservoir that allows us to downpour a solution of water and alcohol at the bottom of the hole, without having the solution freeze before reaching the bottom," said Laurent.

"This allows us to drill for 2-3 days in fairly good conditions," explained Laurent.

"I don't think it will be possible to reach the bedrock this season," he said, "but I am confident that we are on the right way to go deeper and deeper."

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Lucia Simion is a freelance journalist and photographer based in Paris. This was her third visit to Dome C.

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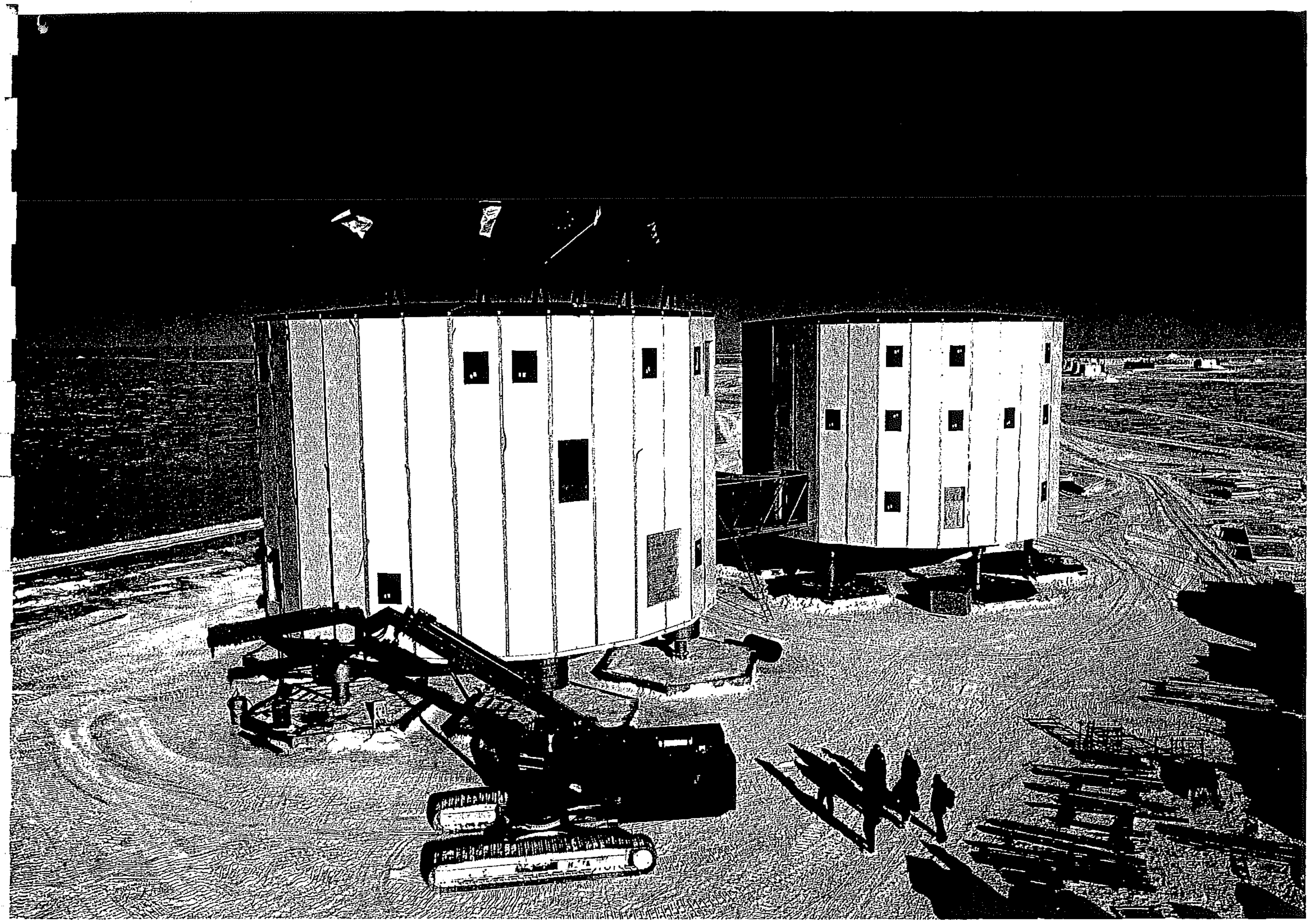
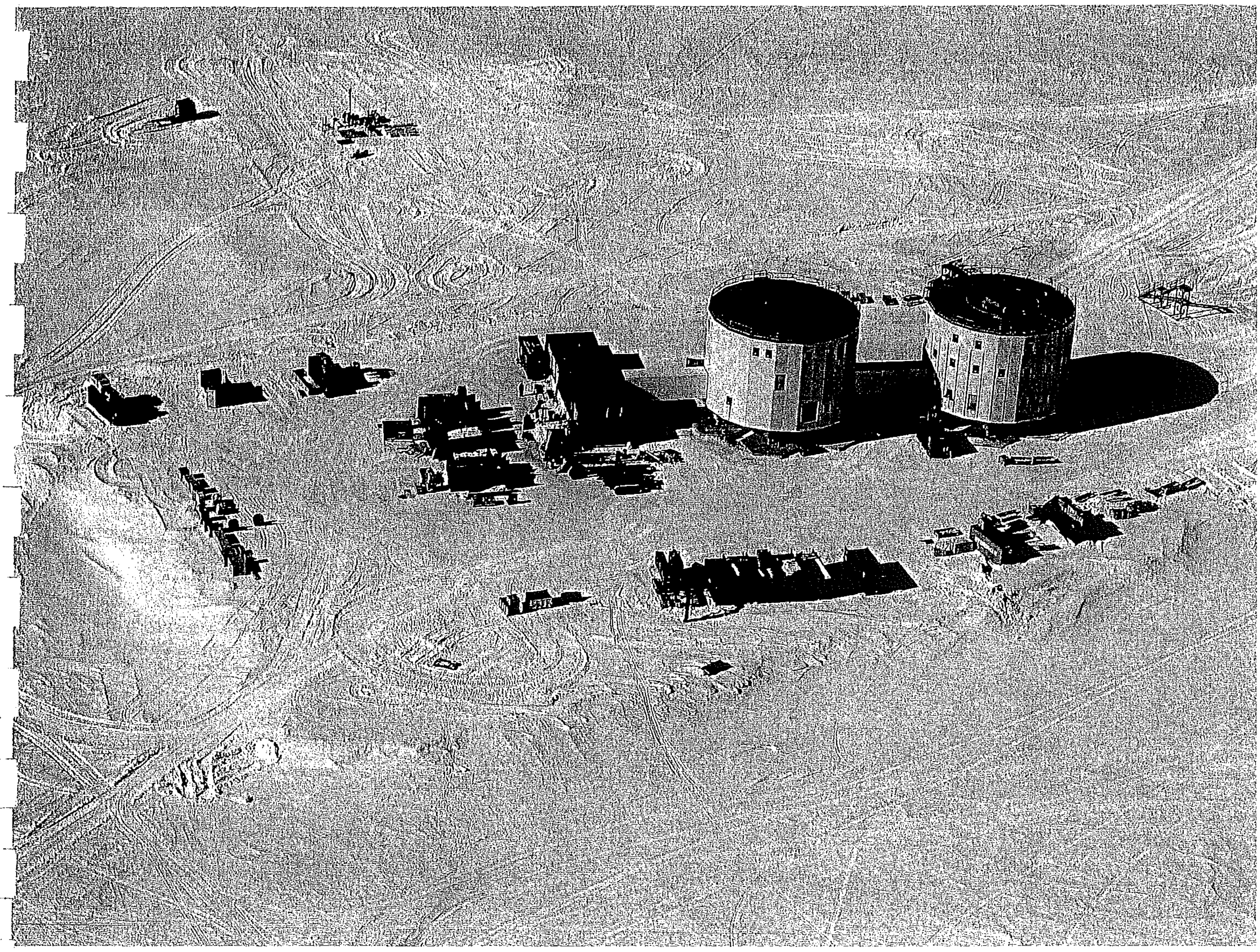
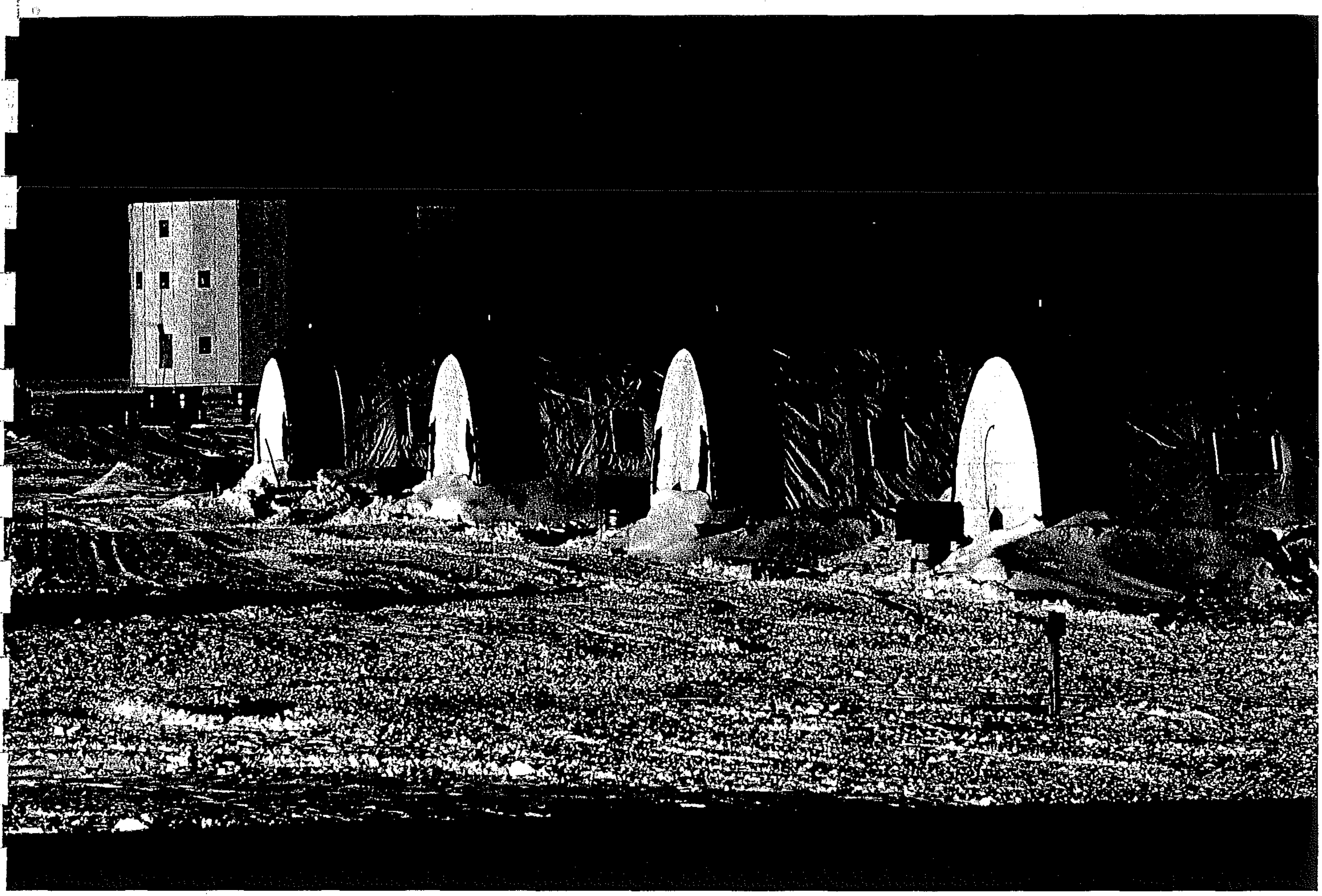
The Concordia Station in Dome C



Dome C: The French-Italian Concordia station in december 2003.
Ph. Lucia Simion



Dome C: The French-Italian Concordia station in january 2004. The small building on the left side is the Power Room. Ph. Consorzio PNRA.



Dome C: The dormitories-tent of the summer camp, with the French-Italian Concordia station in the background, January 2003. Concordia was open for the first winter over on February 10th, 2005.
Ph. Lucia Simion

Dome C: The Twin Otter being refuelled prior to the take off from Dome C, destination Mario Zucchelli Station (MZS) at Terra Nova Bay.
Ph. Lucia Simion

Dome C: The "traverse" Dumont d'Urville-Dome C (1.100 Km), arriving at Dome C after a 8-10 days journey. Ph. Lucia Simion

LUCIA SIMION 116, rue La Fontaine-75016 PARIS
Tél. 06 85 83 15 74
Email: luz.simion@wanadoo.fr